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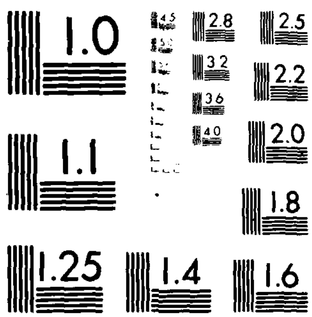

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NSWC TR 81-197

TRANSMISSION OF ULTRASONIC WAVES THROUGH A SOLID LAYER IMMERSED IN LIQUID

BY GEE IN GOO

RESEARCH AND TECHNOLOGY DEPARTMENT

JANUARY 1979

NAVAL SURFACE WEAPONS CENTER

Dahlgren, Virginia 22448 • Silver Spring, Maryland 20910

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This report presents a method using an existing theoretical expression for determining the transmission coefficient of ultrasonic waves incident on a thin plastic plate at an arbitrary oblique angle. The theoretical results were substantiated by inhouse and published data. Frequencies investigated range from 100 to 1000 kHz and materials investigated were Absonic-A, plexiglas and low-density polyethylene.

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FOREWORD

The design and development of liquid filled acoustic lenses necessitated a theoretical method which can accurately predict the transmission coefficient of an acoustic wave propagating through layered media at various angles to the normal. This report describes such a method for determining the transmission coefficients and demonstrates its accuracy against available published data. Funding for this effort was provided by the Naval Sea Systems Command, Task No. S0266001/U13CA.

The author would like to thank Dr. Bruce Hartmann for his guidance in this endeavor, Mr. Paul Huber for his assistance in verifying the accuracy of the method against published data, and Mr. W. Rust, Head, Electrical Design Branch, for reviewing this report.

IRA BLATSTEIN
By direction

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INTRODUCTION

Many materials are used in underwater acoustic systems for items such as transducer windows, acoustic concentrators, acoustic lens, acoustic tank linings, and reflectors. Their application depends strongly on their characteristic properties in transmission, reflection, and absorption. The continuous development in sonar domes and acoustic lens necessitated the investigation of ultra-sonic wave through single and multilayered thin plastic materials. Until recent years there has been limited experimental data and theoretical results. Often the transmission and reflection coefficients are measured instead of calculated. To date, there seems to be several methods available for theoretically approximating the transmission characteristics of the acoustic materials. This report presents one of the methods and its calculated results.

One of the many applications of acoustic materials in underwater acoustics is in the construction of acoustic lens. In particular, this program has an interest in a spherical liquid filled lens as diagrammed in Figure 1. A liquid-filled spherical lens basically consists of a thin plastic shell of the desired transmittion coefficient and a liquid of the desired index of refraction (η_2). It has the properties of converging the acoustic rays toward a focal point along the lens axis as shown in Figure 1. Its focal distance, f, from center of the spherical lens is directly related to the index of refraction of the lens liquid.

To select the proper acoustic window for an acoustic lens, it is necessary to select the transmission characteristics of alternative materials. These characteristics are evaluated on the basis of determining the percentage of sound transmitted through and reflected from the sample material immersed in a liquid media. Through the transmission characteristic of a material, one can predict the approximate aperture of an acoustic lens. For a desired aperture, material of certain transmission characteristic will be selected. Having selected a desired aperture one would have defined the desired operational characteristic such as beam width of the acoustic lens.

The problem of transmission and reflection of ultrasonic waves through layered media has been treated by many authors. The theoretical treatment dates back to W. T. Thomson[1] in 1950. In his paper, he treated the transmission and reflection problem as a boundary value problem. At the boundary, the stress and

[1]Thomson. W., "Transmission of Elastic Waves Through a Stratified Medium," J. Appl. Phys. 21, 89-93, 1950.

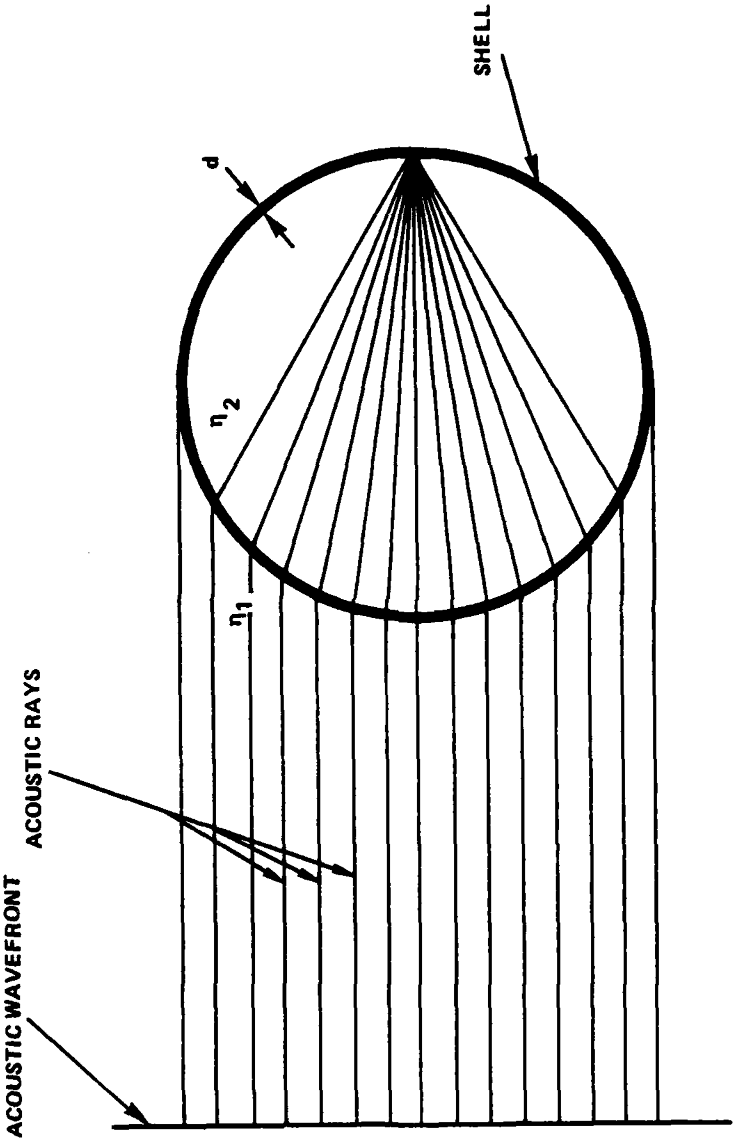

FIGURE 1 ACOUSTIC LENS

particle velocity are assumed to be continuous. Brekhovskikh's[2] treatment paralleled that of Thompson's and yields a similar expression which is valid only to limited cases; i.e., single-layer problem as indicated by Mr. D. Folds.[3] In 1953, Haskell[4] correctly formulated an expression which is applicable to multilayered cases. Since our interest is a single solid layer immersed in a liquid media and because Brekhovskikh's solution is a widely used reference by many researchers, we have employed his expression for this analysis.

[2] Brekhovskikh, L. M., "Wave in Layered Media," Academic, New York, 1960.

[3] Folds, D. L. and Loggins, C. D., "Transmission and Reflection of Ultrasonic Waves in Layered Media," J. Appl. Soc. Am. 62, 1102-1109, 1977.

[4] Haskell, N., "The Dispersion of Surface Waves in Multilayered Media," Bull. Seismol. Soc. Am. 43, 17-34, 1953.

THEORY

Paralleling Brekhovskikh's development with Mr. P. Huber's assistance the same expressions were derived for a single solid layer surrounded by a liquid media as D. Folds and Barnard, et al[5] had indicated in their papers. The transmission (t) and reflection (r) coefficient expressions for a single solid layer surrounded by liquid media as diagrammed in Figure 2 are given by:

$$T = \frac{2\,N\,Z}{M\,(Z_1 + Z_3) \;+\; i(N^2 - M^2)\,Z_1 + Z_3}$$

$$R = \frac{M(Z_1 - Z_3) \;+\; i(N^2 - M^2)\,Z_1 - Z_3}{M\,(Z_1 + Z_3) \;+\; i(N^2 - M^2)\,Z_1 + Z_3}$$

where M, N, and Z's are expressed as:

$$M = \frac{Z_2}{Z_1}\,\mathrm{Cos}^2\,2\gamma_2\;\;\mathrm{Cot}\;P + \frac{Z_{2t}}{Z_1}\cdot \mathrm{Sin}^2\,2\gamma_2 \cdot \mathrm{Cot}\;Q$$

$$N = \frac{Z_2}{Z_1}\;\frac{\mathrm{Cos}^2\,2\gamma_2}{\mathrm{Sin}\;P} + \frac{Z_{2t}}{Z_1}\cdot\frac{\mathrm{Sin}^2\,2\gamma_2}{\mathrm{Sin}\;Q}$$

and

$$Z_1 = \frac{\rho_1\,c_1}{\mathrm{Cos}\;\theta_1}$$

[5]Barnard, G., Bardin, J. L. and Whiteley, J. W., "Acoustic Reflection and Transmission Characteristics for Thin Plates." J. Acoustic Soc. Am. 57. 577-584, 1975.

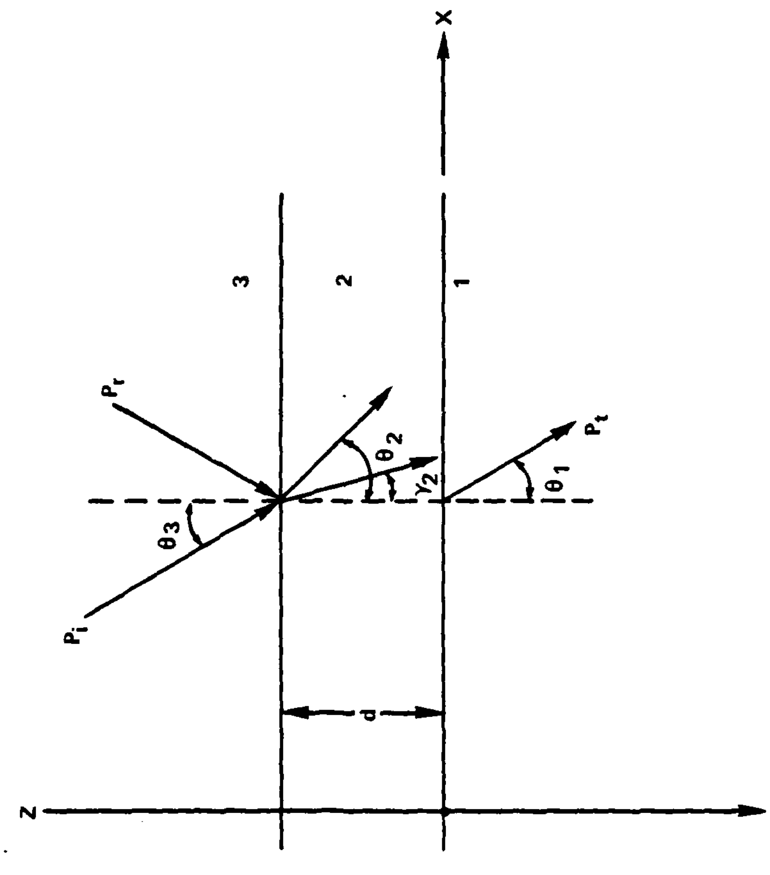

FIGURE 2 SINGLE SOLID LAYER PROBLEM

$$Z_2 = \frac{\rho_2 c_2}{\cos \theta_2}$$

$$Z_3 = \frac{\rho_2 c_3}{\cos \theta_3}$$

$$Z_{2t} = \frac{\rho_2 b_2}{\cos \gamma_2}$$

where the subscripts 1, 2, and 3 indicate the medium of interest while 2t represents the shear (transverse) mode of propagation in solid layer, media 2. Also, ρ's are the densities and c's and b's are the velocities of the respective media. P and Q are two "dummy" variables which are related to the propagation constant for the longitudinal wave, α, shear wave, β, and thickness, d, of the sample material

$$P = \alpha d$$
$$Q = \beta d$$

Since α represents the z-component of the propagational constant k_2 of the longitudinal wave while β is the like quantity K_2 of the shear wave, thus α and β can be expressed as

$$\alpha = -k_2 \cos \theta_2$$

$$\beta = -K_2 \cos \gamma_2$$

where θ_2 and γ_2 are related to the incident angle θ_3 by the Snell's Law

$$k_3 \sin \theta_3 = k_2 \sin \theta_2 = k_1 \sin \theta_1 = K_2 \sin \gamma_2$$

θ_3, θ_2, θ_1, and γ_2 are measured with respect to the normal to the plane of the solid layer and these quantities may be complex. Thus, the quantities P an Q can be rewritten as;

$$P = -k_2 d \cos \theta_2$$

$$Q = -K_2 d \cos \gamma_2$$

Note that k_2 and K_2 are wave numbers in the longitudinal and shear mode which are given respectively by

$$k_2 = \frac{W}{c_2}$$

$$K_2 = \frac{W}{b_2}$$

$$W = 2\pi \bullet f$$

where c_2 and b_2 are respectively the longitudinal and shear sound velocities in the solid layer of thickness, d, and f is the frequency of interest.

Since absorption is present in most solid materials and it is related to the sound velocity c and b in the solid by the expression below

$$c = \frac{c_o}{(1 + \phi_c^2)^{1/2}} \, EXP\,(i \tan^{-1} \phi_c)$$

where

$$\phi_c = \frac{c_o}{W}$$

α and β are redefined as the absorption constants expressed in neper/ft. The absorption can be related to the attenuation by

$$\alpha = a \,/\, 8.6858$$

where a is the attenuation in db/ft. Note that c_2 and b_2 are now complex quantities. It is indeed difficult to image physically that the sound velocity and reflected angles in the solid layer as complex quantities.

EXPERIMENTAL DATA

The experimental test set up at NAVSURFWPNCEN acoustical facility is basically that of References 3, 5, and 6, except for the collimator lens which was used as diagrammed in Figure 3. The collimator was used to insure that the impinging wave at the sample plate would be a plane wave (far-field effect). The receive hydrophone E-27 is located close to the sample plate to avoid edge effects; yet far enough to avoid standing waves between the hydrophone and the sample plate. The test sample plate was a 24-inch square and hydrophone locations are as shown in Figure 4.

Since only limited experimental measurements were made at NSWC and the sound velocities and test material are not known, experimental data used to verify calculated results were basically from References 3 and 6. Figure 5 to Figure 8 show results from Reference 3 versus NSWC calculated results. Figure 9 to Figure 16 show the data from Reference 3 versus NSWC calculated results. The material parameters from References 3 and 7 used in the theoretical calculations are listed in Table 1.

[3] See footnote 3 on page 9.

[5] See footnote 5 on page 11.

[6] Nichols, R. H., "Acoustic Properties of Rho-C Rubber and ABS in the Frequency Range 100 kHz - 2 MHz," J. Acoustic Soc. Am. 54, 1763-1765, 1973.

[7] Hartmann, B. and Jarznyski, J., "Immersion Apparatus for Ultrasonic Measurements in Ploymers," J. Acoustic Soc. Am. 56, 1479-1477, 1974.

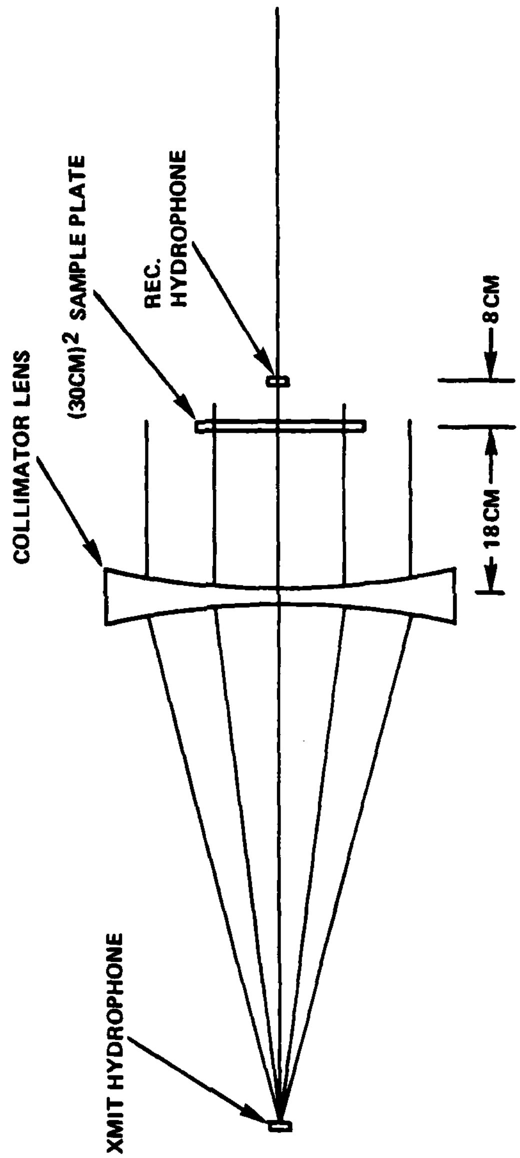

FIGURE 3 EXPERIMENTAL SETUP

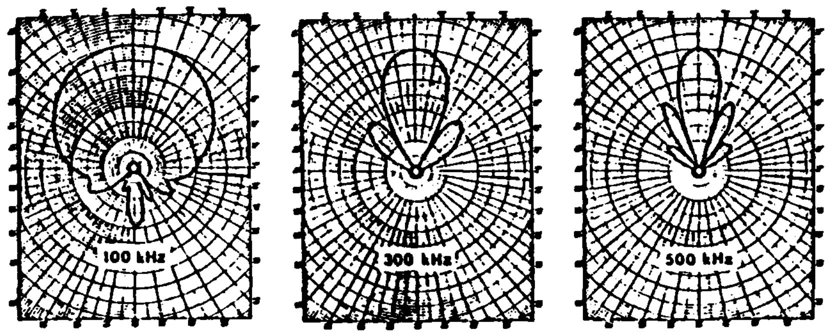

FIGURE 4 DIRECTIVITY, TYPE E27 TRANSDUCER, IN PLANES THAT INCLUDE THE X AXIS. SCALE: CENTER TO TOP OF GRID EQUALS 50 dB.

RESULTS

Brekhovskikh's expression was used in the theoretical calculation to predict the transmission coefficients. To better estimate the coefficients, two assumptions were made. First, the velocities c and b were allowed to be complex; thus, the wave numbers in the solid layer k_2 and K_2 are also complex. These complex quantities were used throughout the calculations. Secondly, instead of assuming the attenuations in the longitudinal and shear modes, α and β respectively are the same, they are assumed to have the relation of

$$\frac{\alpha}{\lambda_\ell} = \frac{2\beta}{\lambda_s}\left(\frac{b}{c}\right)^2$$

Since λ_ℓ and λ_s, the respective wavelength, are defined as

$$\lambda_\ell = \frac{c}{f}$$

$$\lambda_s = \frac{b}{f}$$

thus, the above can be rewritten as

$$\alpha = 2\beta\left(\frac{b}{c}\right)$$

and β can be expressed as

$$\beta = \frac{\alpha}{2}\left(\frac{c}{b}\right)$$

Throughout the development of the method of approximation it has been observed that the correct sound velocity measurements are very important. For example, in determining the theoretical transmission coefficient for Absonic-A at 19.1°C of Reference 5, there was no difficulty arriving at the same data as the measured data when measured parameters of Reference 5 were used. These results were shown in Figures 5 through 8. However, if other published

[5]See footnote 5 on page 11.

values were used for the Absonic-A sound velocities, the calculated results were very different from the measured data. In the case of Reference 3, using the values in Table 1, the calculated transmission coefficient was a good approximation of the published measured data for a single solid layer. This is shown in Figure 9 for LDPE; Figures 10 through 13 for plexiglas; and Figures 14 and 15 for ABS.

It is evident from this theoretical investigation that the material transmission coefficient is dependent on frequency, temperature and thickness of solid layer. For example, Figures 10 through 13 show the effect on the transmission coefficient of a 0.1 inch thick plexiglas plate as a function of frequency. A similar effect is shown on Figures 5 through 8 and Figures 10 through 18 for Absonic-A (ABS). This frequency effect is observed both theoretically and experimentally as shown in these plots. Since sound velocity changes as a function of temperature, one could expect some change in the transmission coefficient. In the case of the materials considered, the temperature effect is amplified greatly because sound velocity increases with increase of temperature in the liquid (water) while the contrary exists in the solid layer. The observed results are shown in Figures 19 though 23 for low-density polyethylene (LDPE). However, material with low thermal coefficients such as ABS has very little effect due to temperature change as shown in Figures 24 through 26. Thus careful selection of material could reduce the temperature effect on the transmission coefficient. Lastly, thickness of the shell also has some effect on the transmission coefficient as shown in Figures 27 through 36. From these plots one could observe the changes on transmission coefficient as a functon of thickness.

Aperture shading is well known and has been used successfully in optics and underwater acoustics. In general, aperature shading is used to improve the directivity response of an acoustic system. The transmission coefficient on an acoustic lens shell has the same effect as that of a shading function. Thus, a lens of a certain operating characteristic would require a certain desired transmission coefficient on its shell. Through careful consideration of the material, thickness, frequency, and operating temperature range, a lens shell can be selected to exhibit a desired transmission coefficient with aperture.

[3]See footnote 3 on page 9.

CONCLUSION

It is evident from this investigation that the acoustic transmission and reflection coefficient of a thin plate can be accurately predicted by employing the Brekhovskinkh's expressions in conjunction with an accurately determined sound velocity in the thin plate material. Thus, this technique can be useful in assisting the selection of acoustic material for acoustic lens of the operating characteristic desired for the acoustic system.

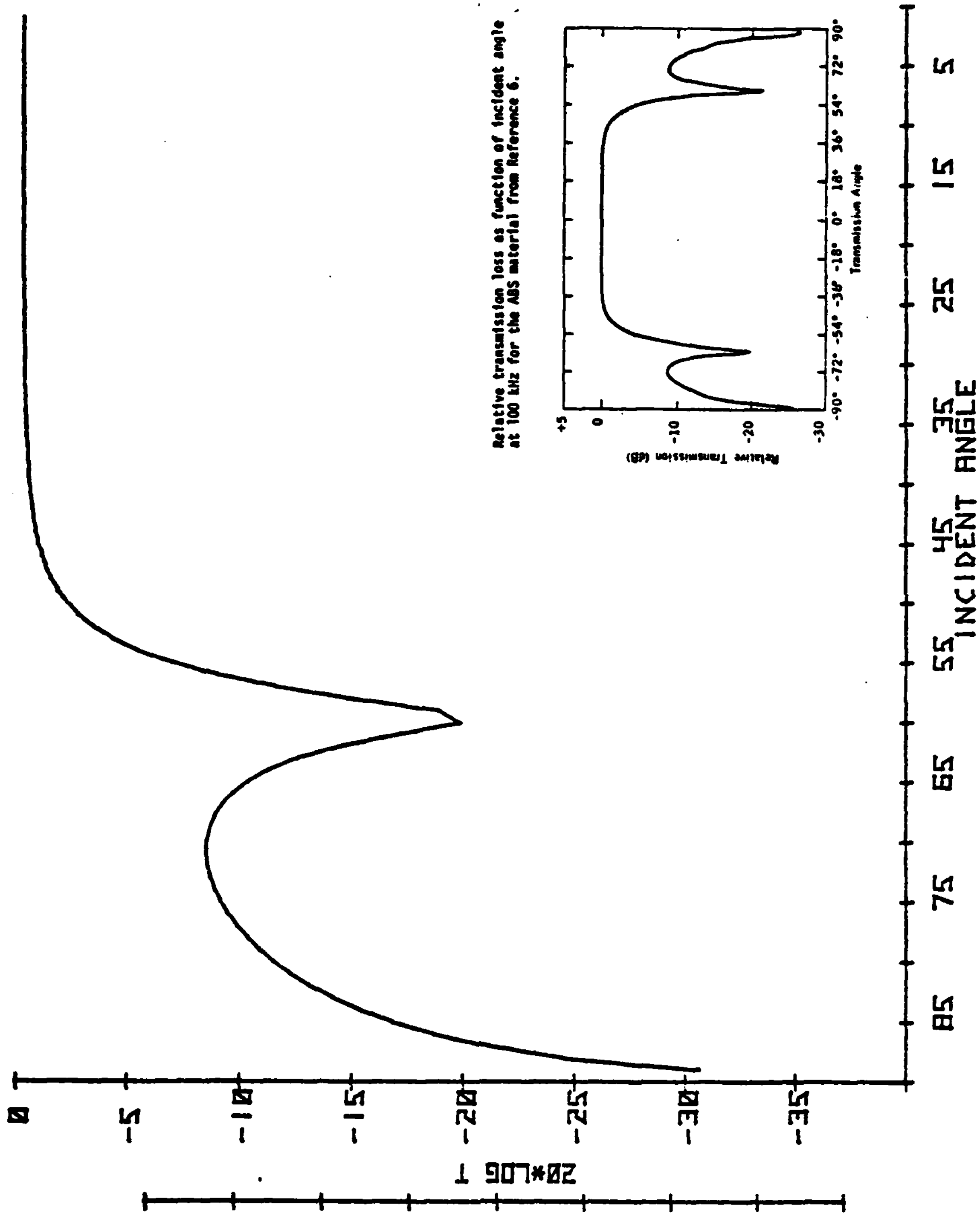

FIGURE 5 TRANSMISSION LOSS AS FUNCTION OF INCIDENT ANGLE AT 100 kHz FOR ABS MATERIAL

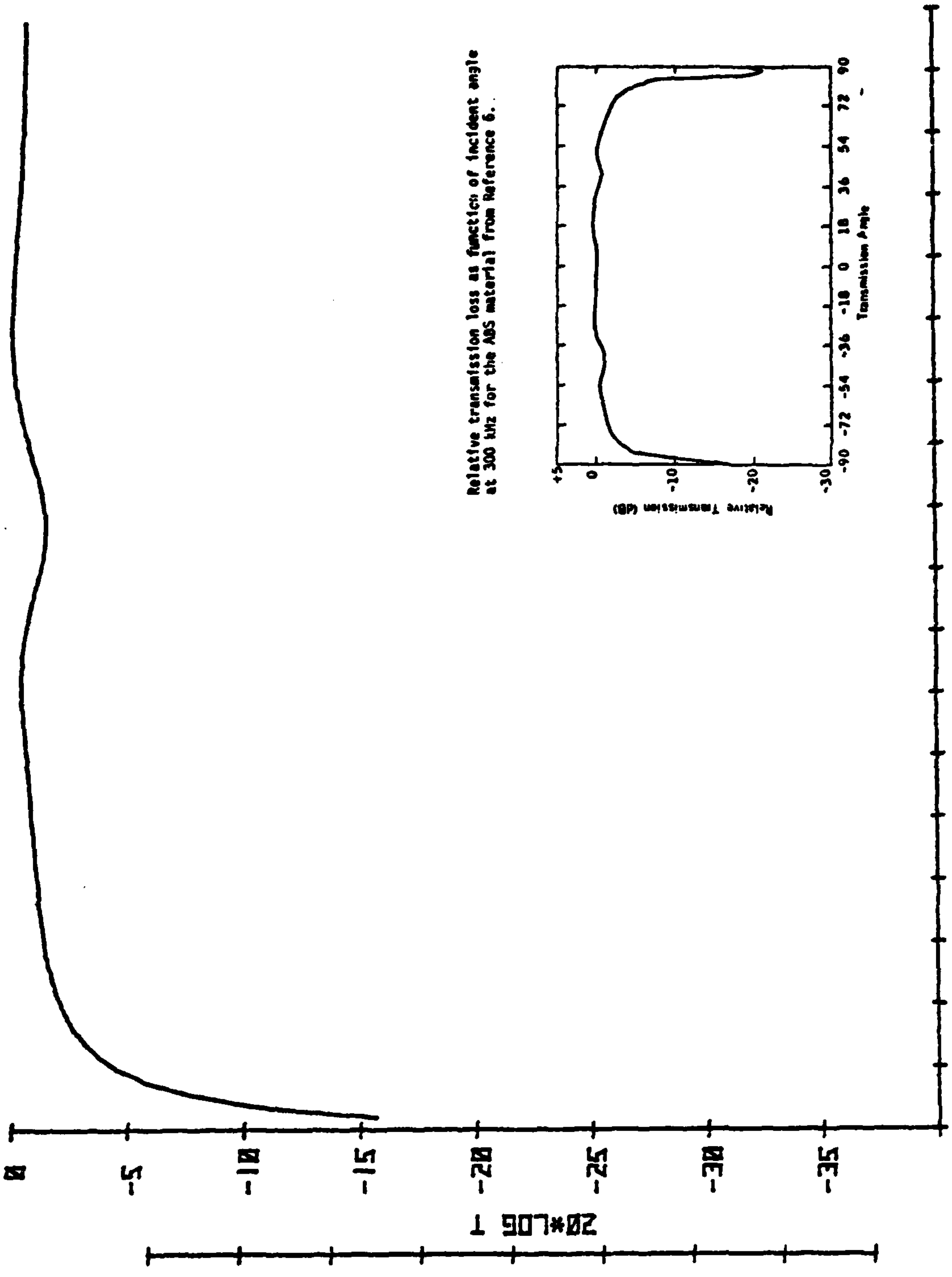

FIGURE 6 TRANSMISSION LOSS AS FUNCTION OF INCIDENT ANGLE AT 300 kHz FOR ABS MATERIAL

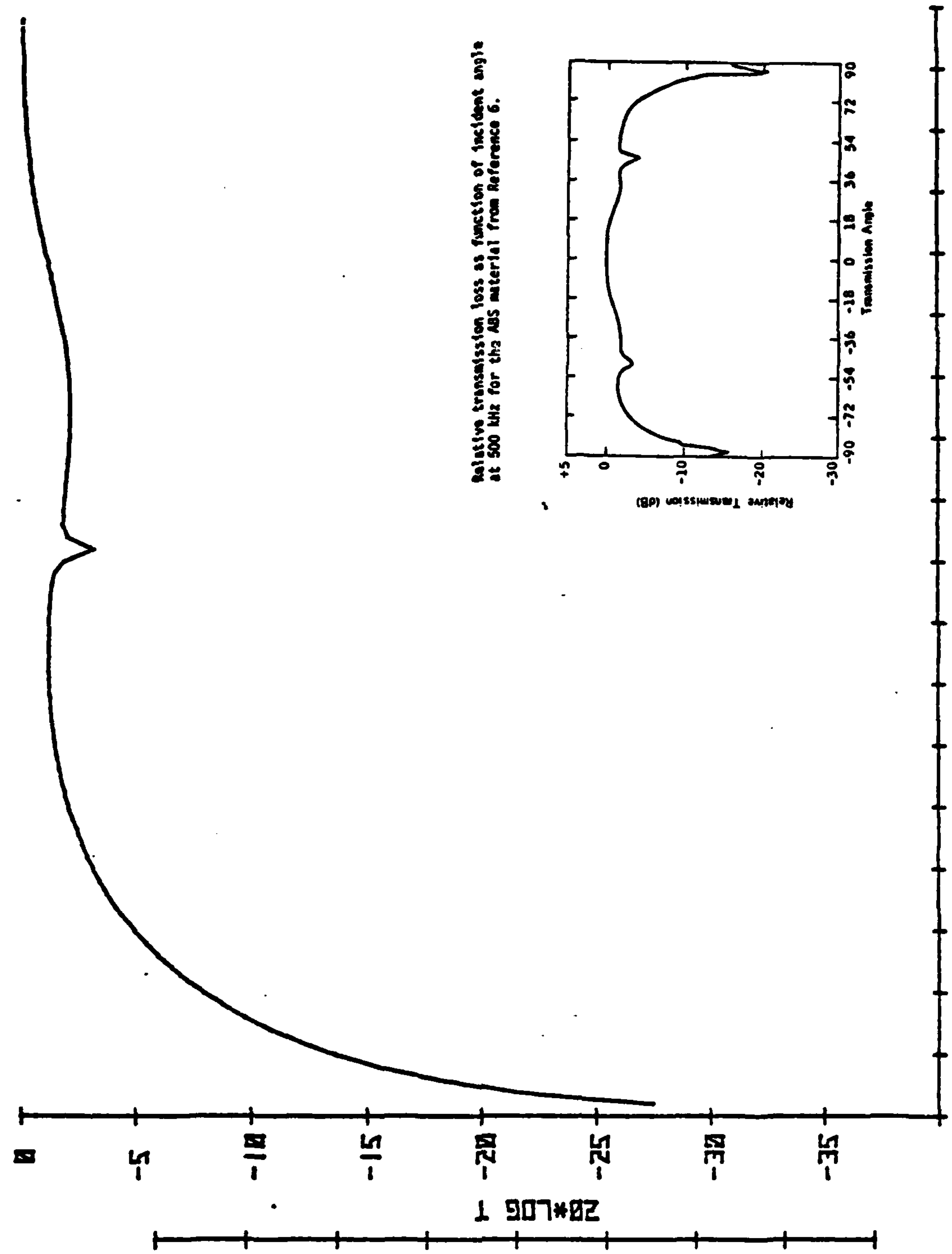

FIGURE 7 TRANSMISSION LOSS AS FUNCTION OF INCIDENT ANGLE AT 500 kHz FOR ABS MATERIAL

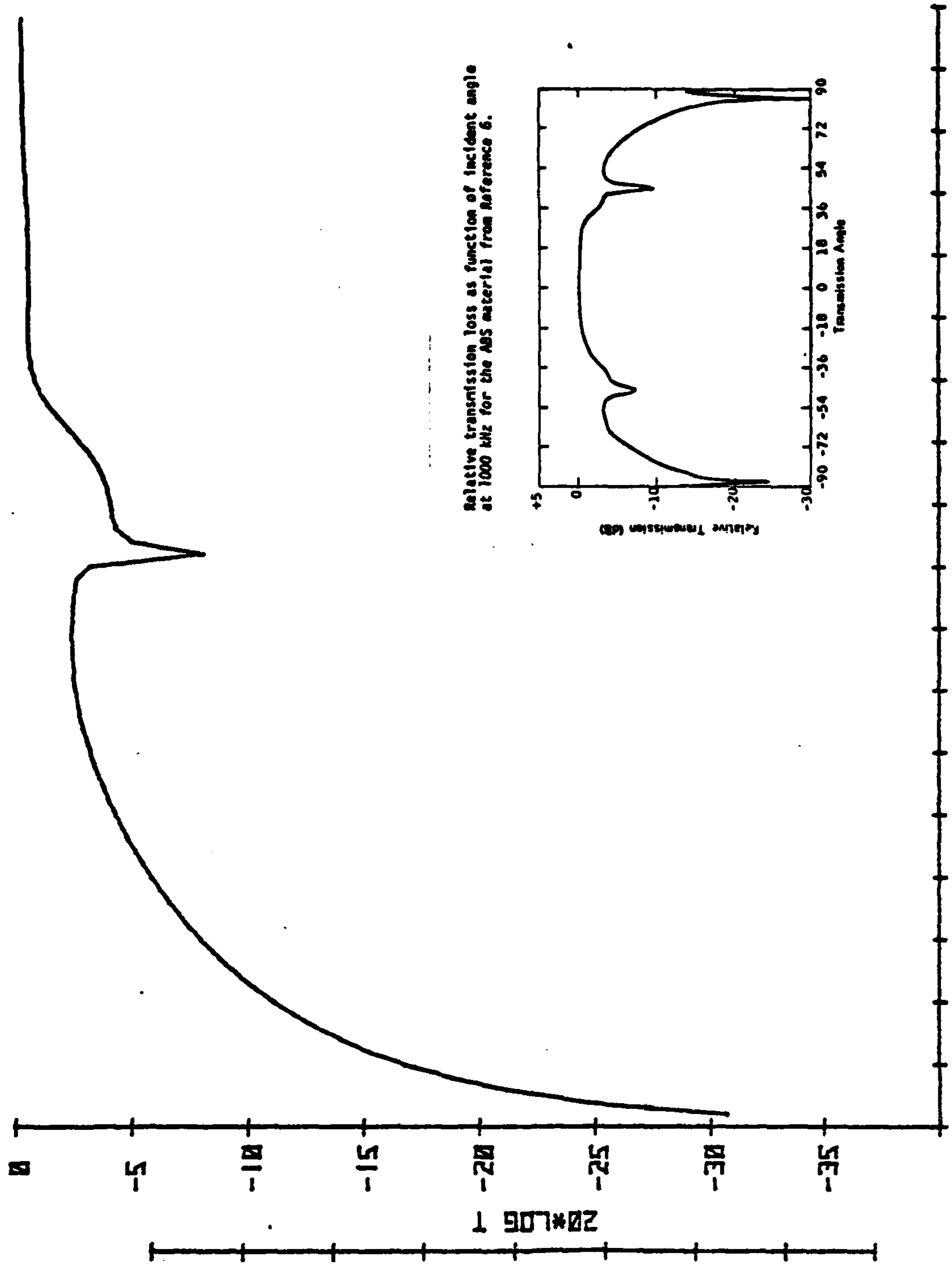

FIGURE 8 TRANSMISSION LOSS AS FUNCTION OF INCIDENT ANGLE AT 1 mHz FOR ABS MATERIAL

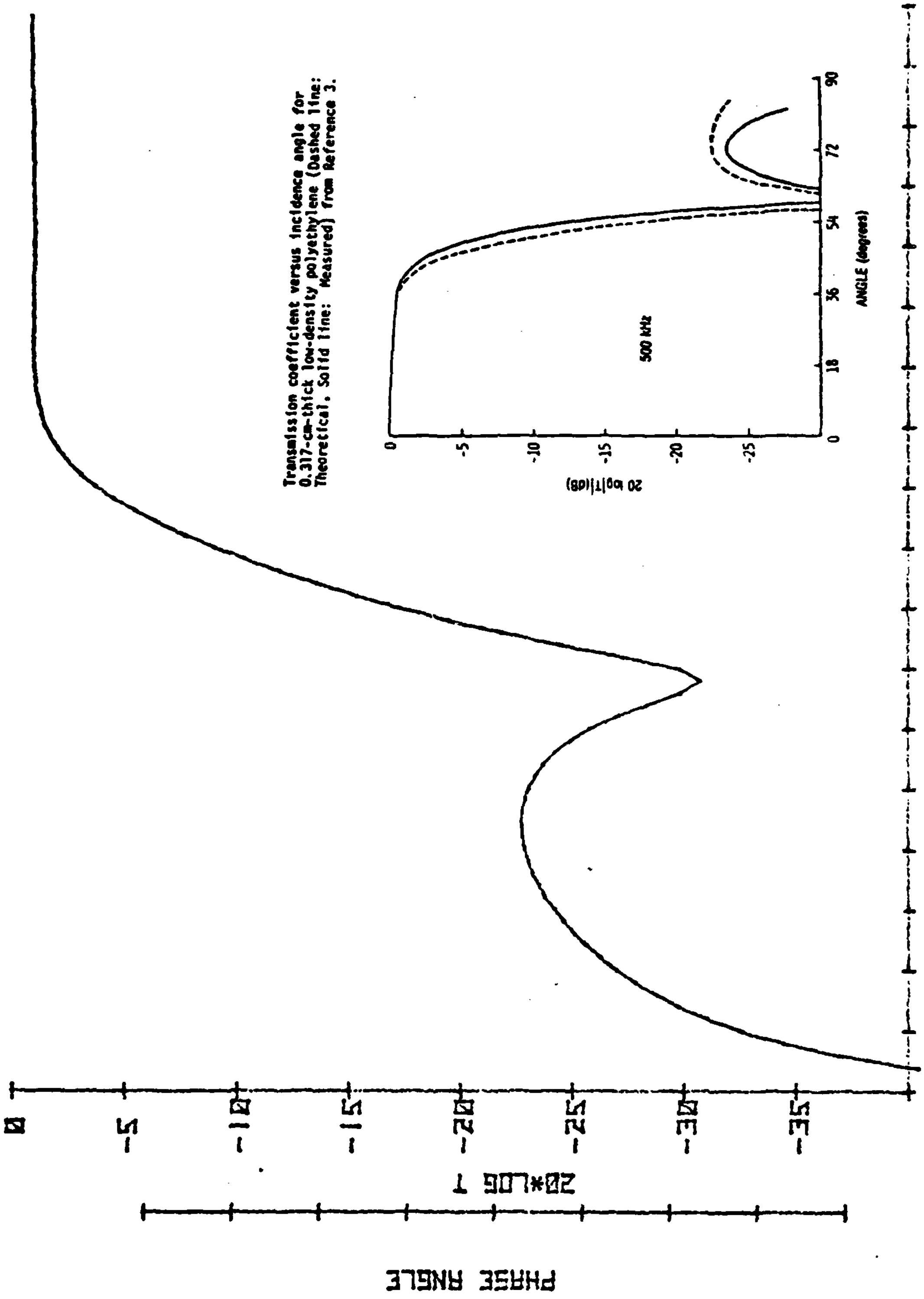

FIGURE 9 TRANSMISSION LOSS AS FUNCTION OF INCIDENT ANGLE AT 500 kHz FOR LOW-DENSITY POLYETHYLENE MATERIAL

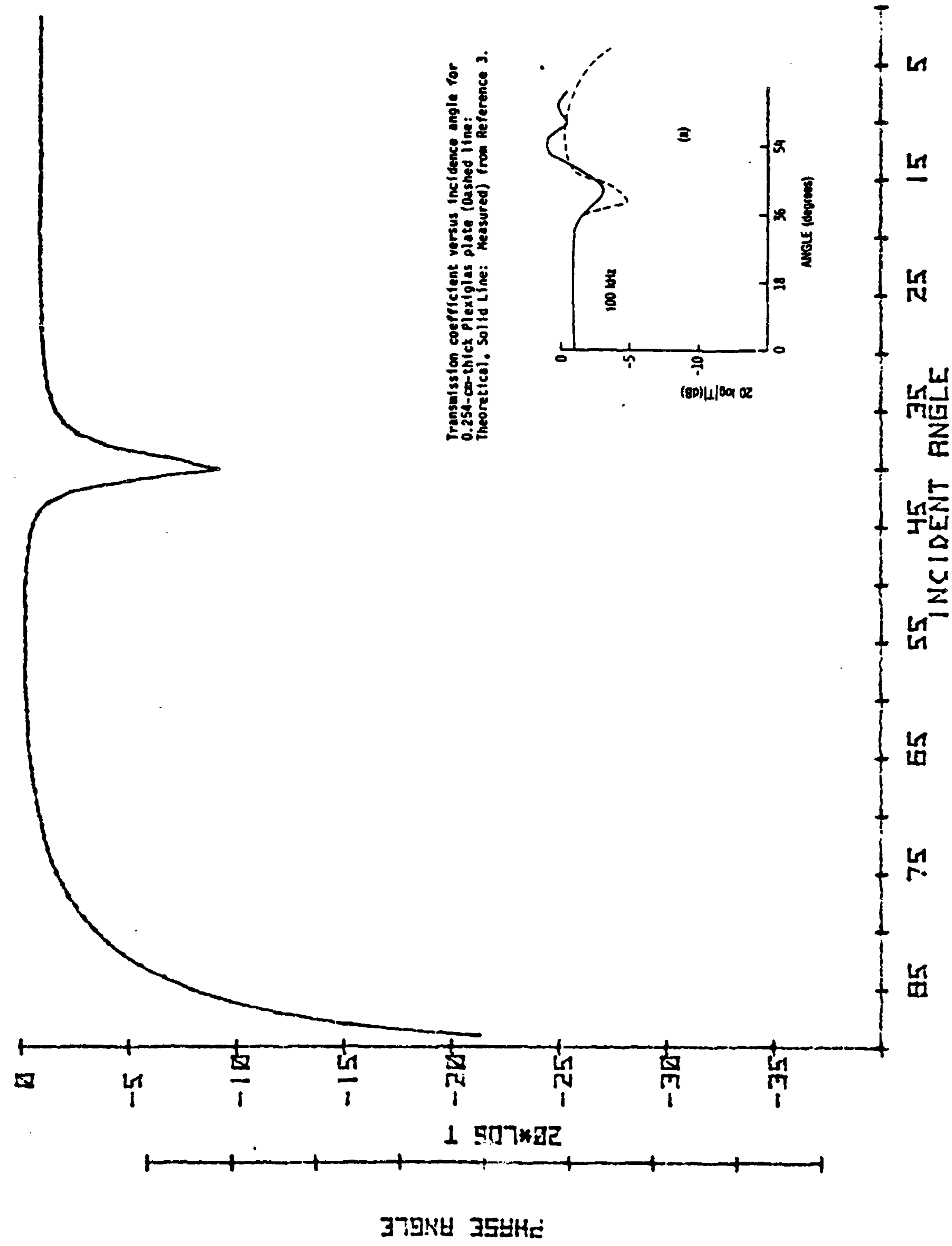

FIGURE 10 TRANSMISSION LOSS AS FUNCTION OF INCIDENT ANGLE AT 100 kHz FOR PLEXIGLAS MATERIAL

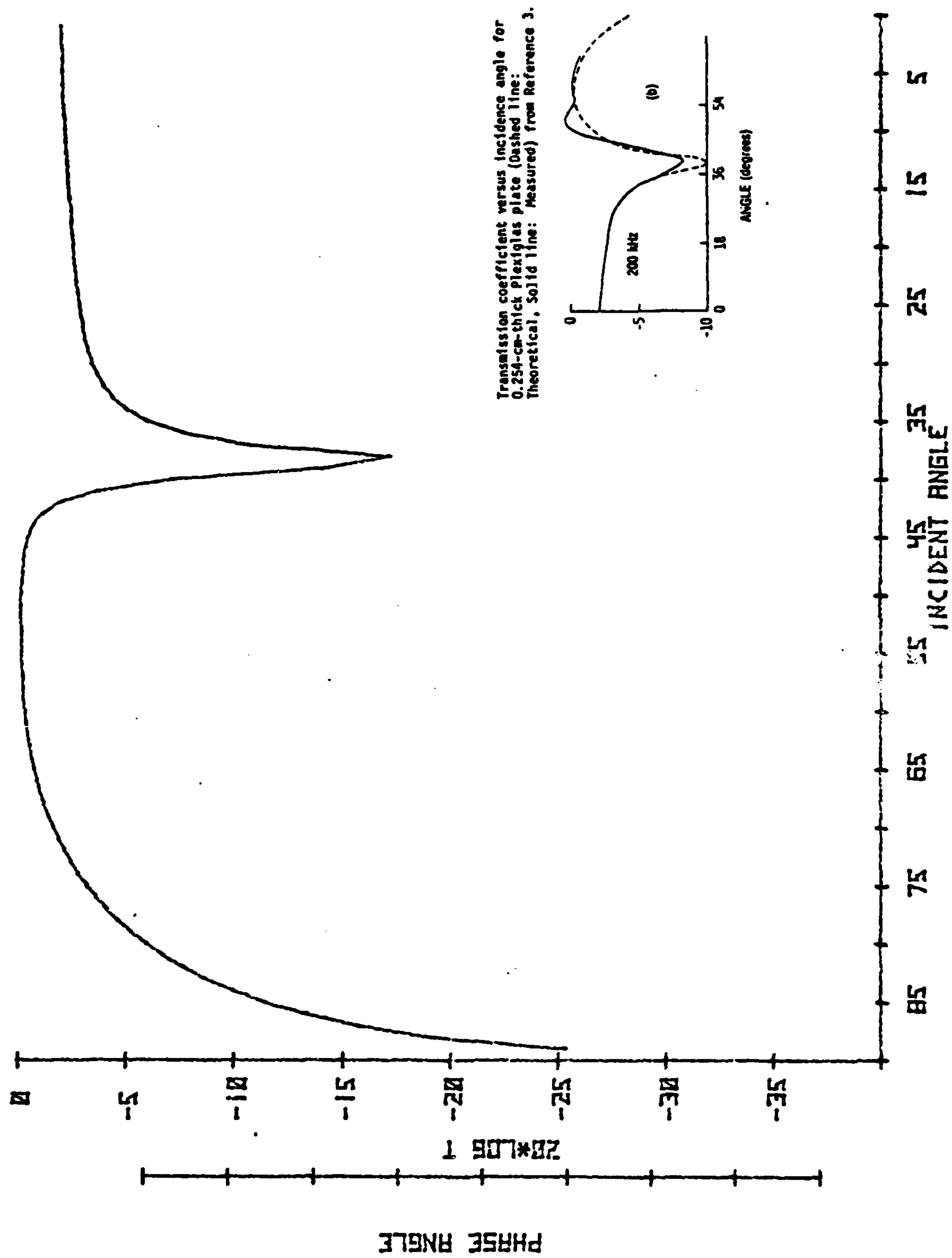

FIGURE 11 TRANSMISSION LOSS AS FUNCTION OF INCIDENT ANGLE AT 200 kHz FOR PLEXIGLAS MATERIAL

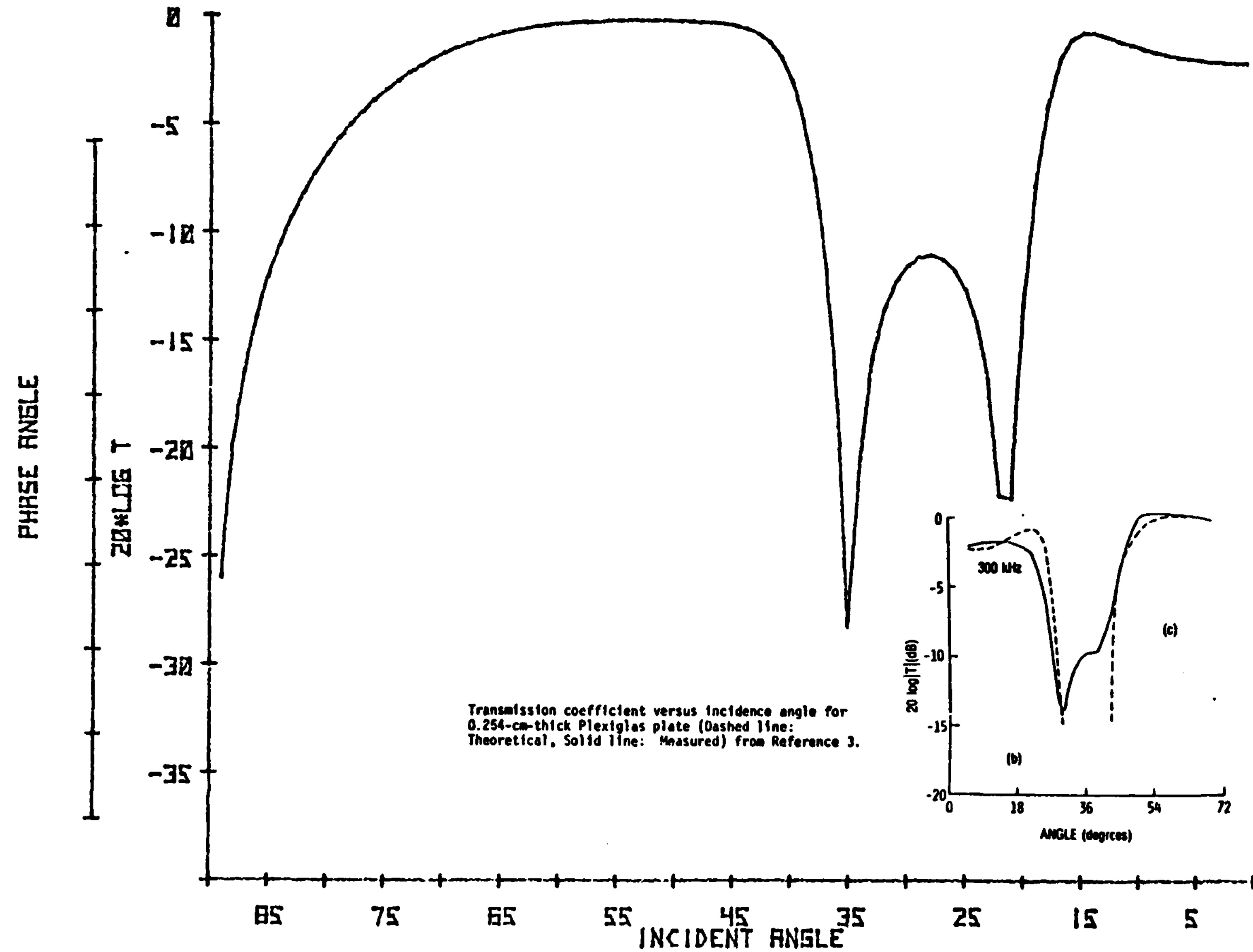

FIGURE 12 TRANSMISSION LOSS AS FUNCTION OF INCIDENT ANGLE AT 300 kHz FOR PLEXIGLAS MATERIAL

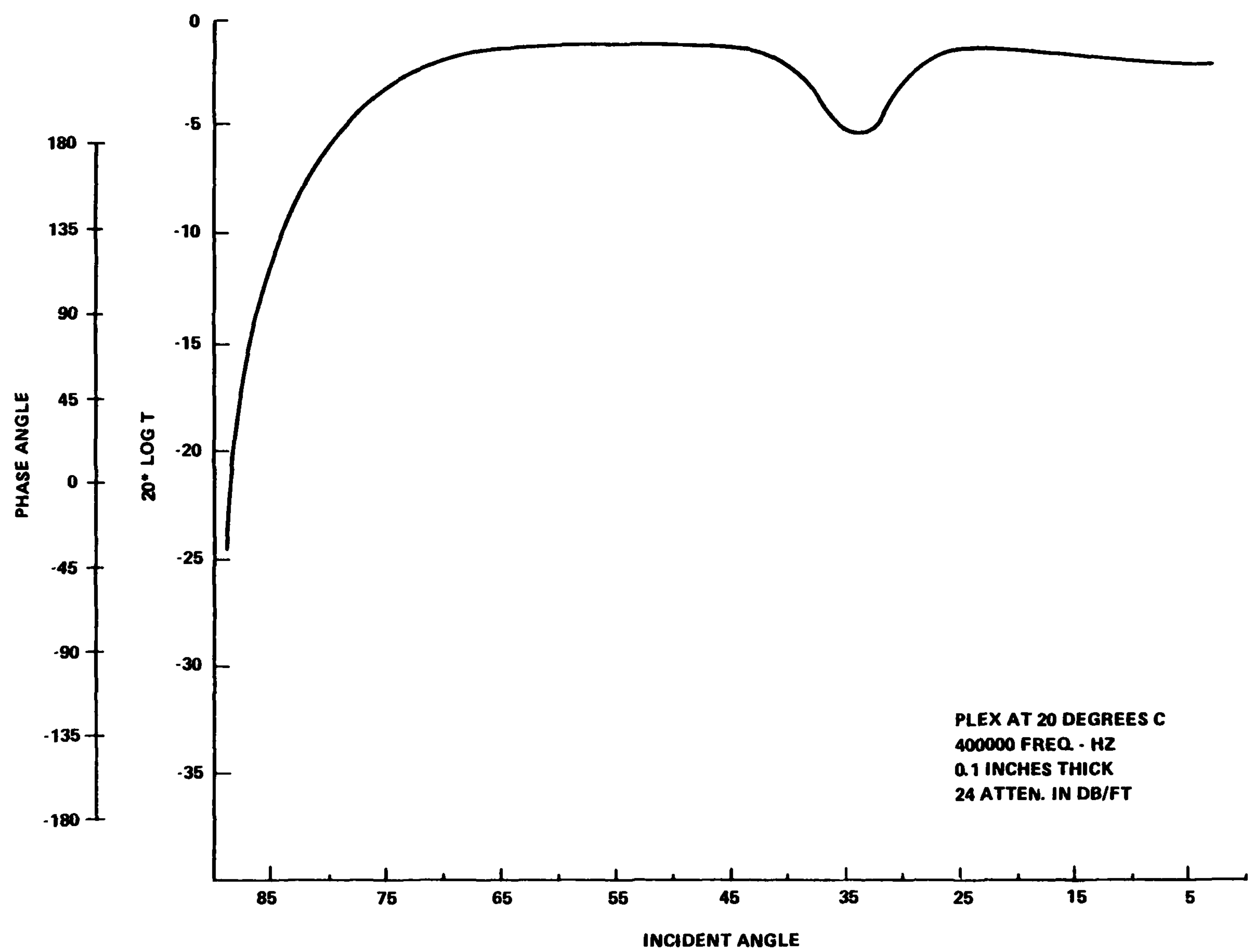

FIGURE 13 TRANSMISSION LOSS AS FUNCTION OF INCIDENT ANGLE AT 400 kHz FOR PLEXIGLAS MATERIAL

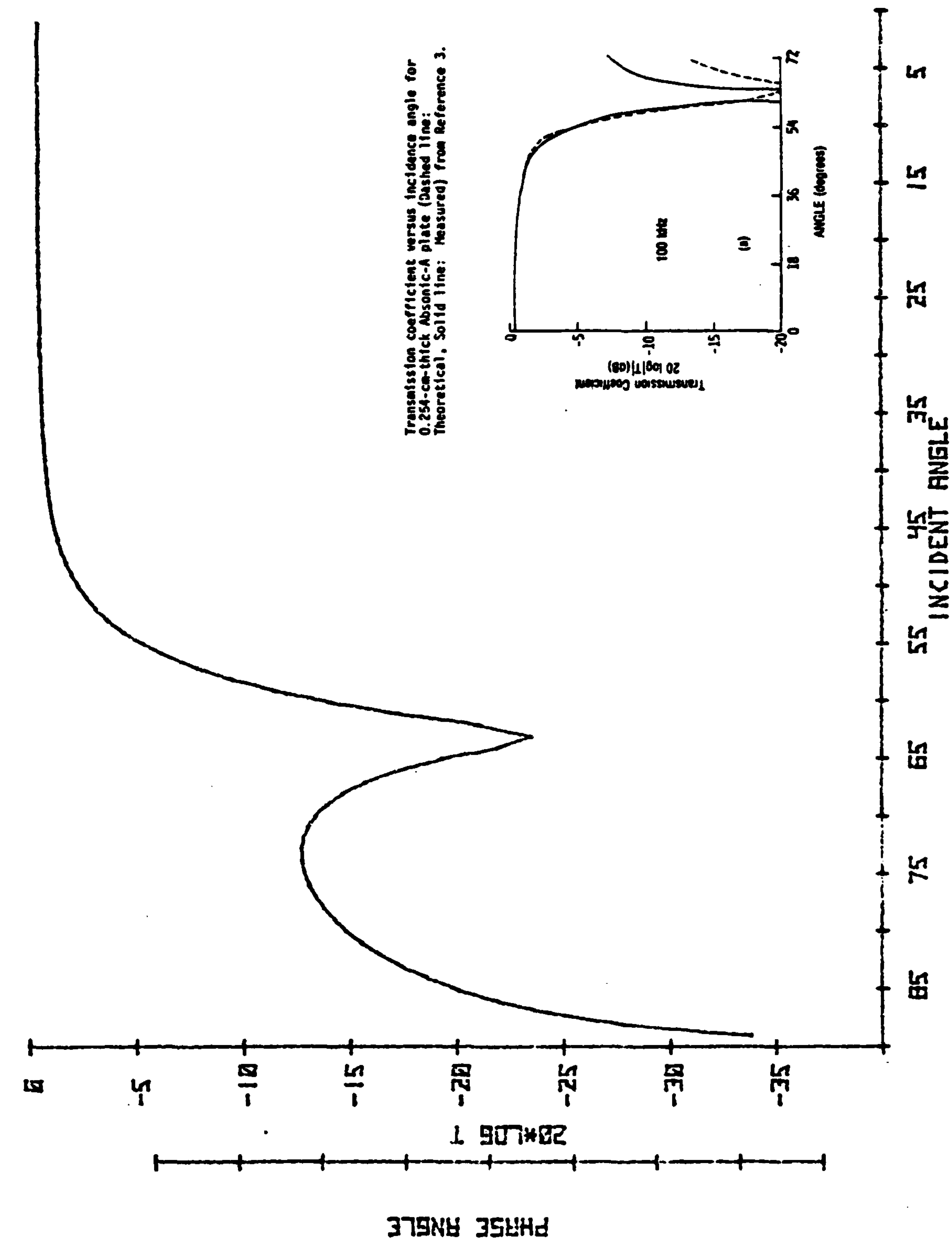

FIGURE 14 TRANSMISSION LOSS AS FUNCTION OF INCIDENT ANGLE AT 100 kHz FOR ABS MATERIAL

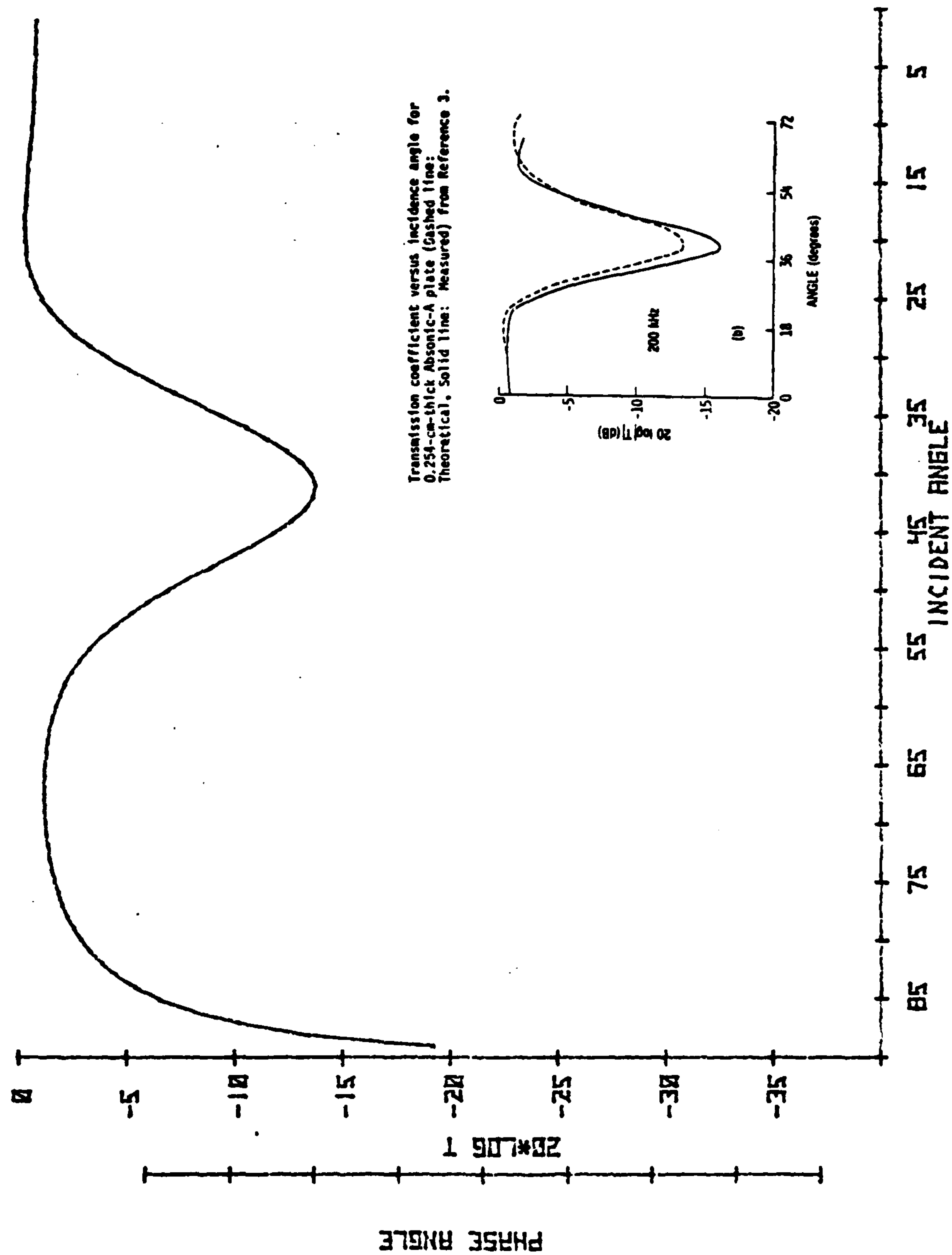

FIGURE 15 TRANSMISSION LOSS AS FUNCTION OF INCIDENT ANGLE AT 200 kHz FOR ABS MATERIAL

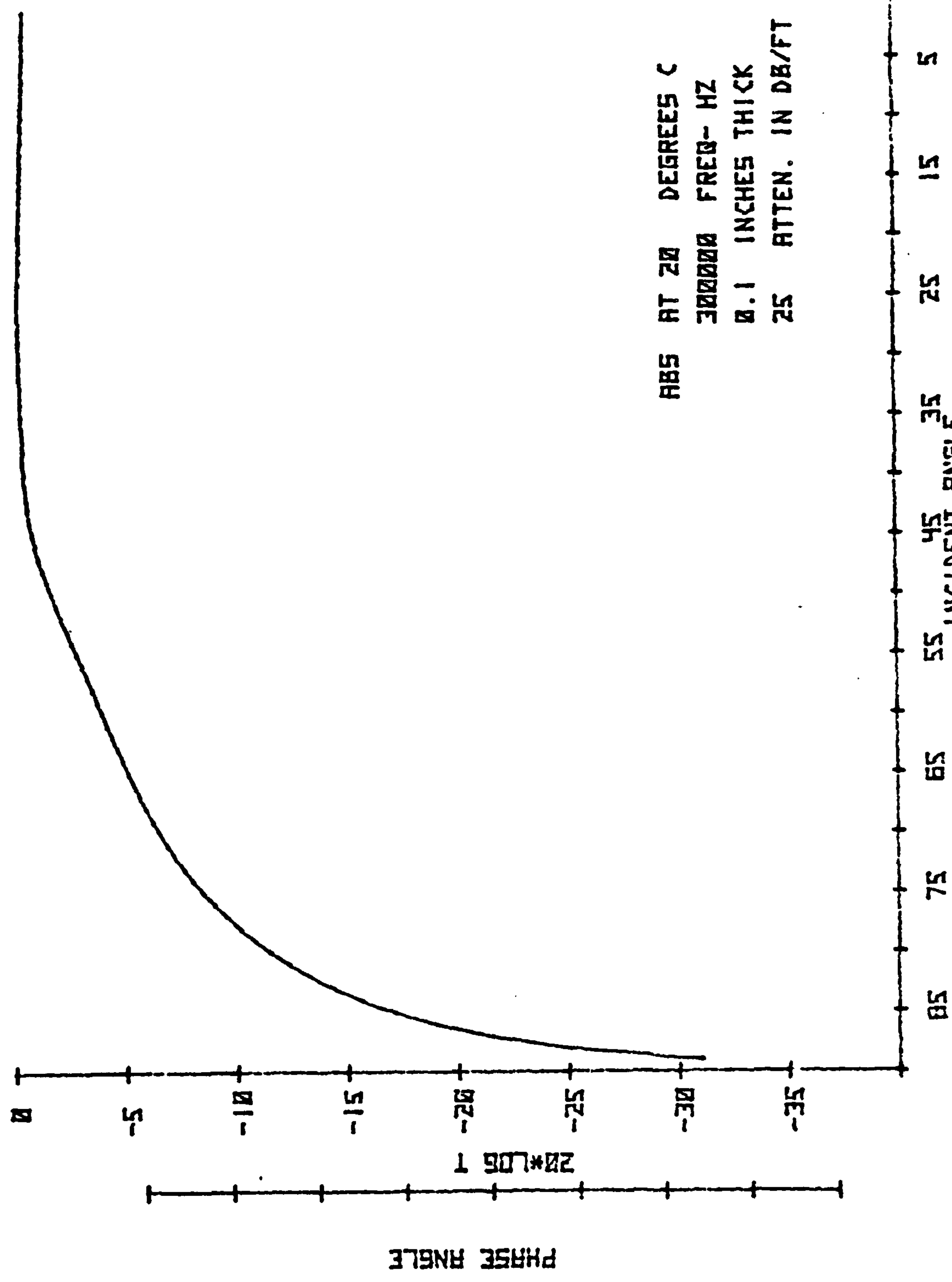

FIGURE 16 TRANSMISSION LOSS AS FUNCTION OF INCIDENT ANGLE AT 300 kHz FOR ABS MATERIAL

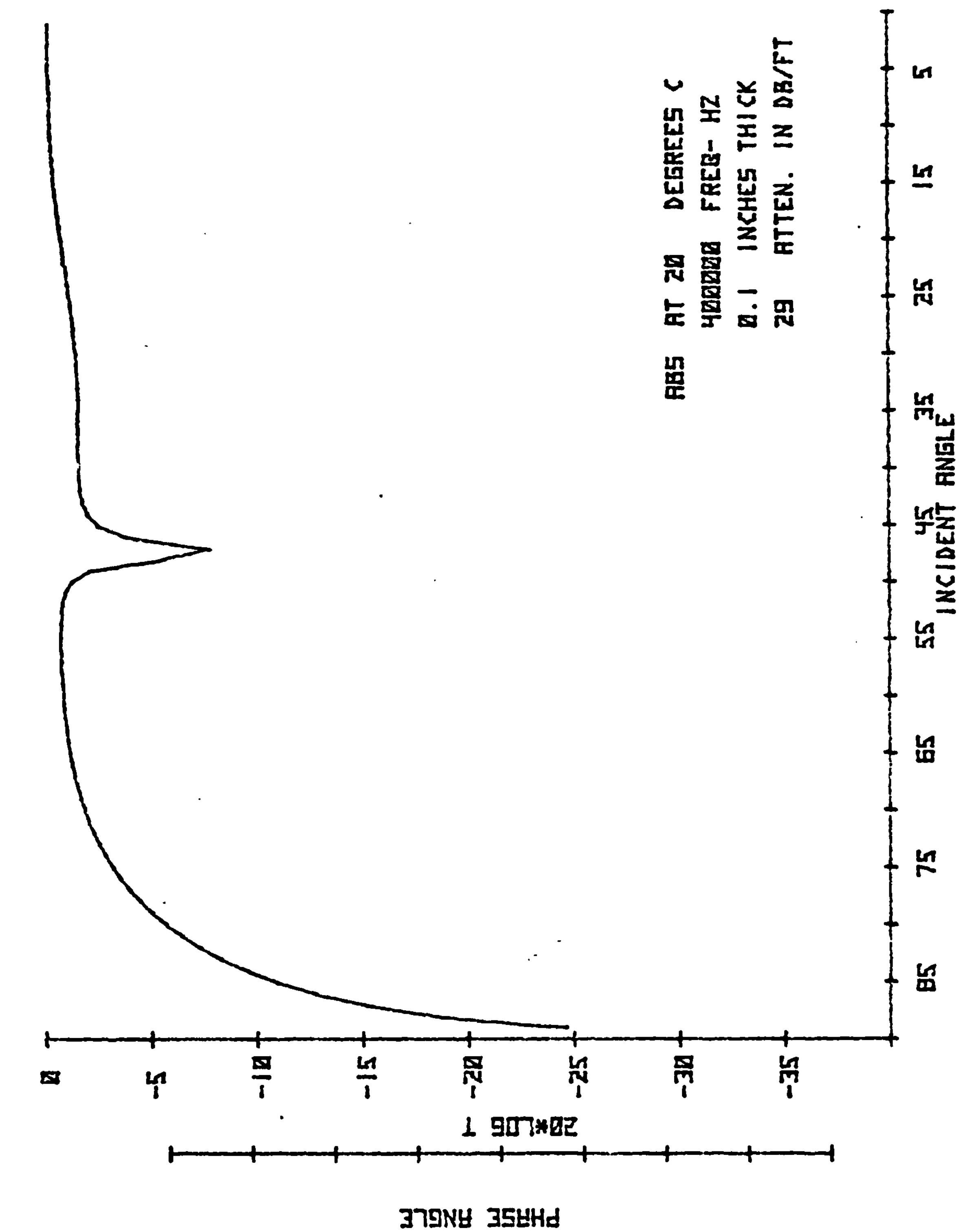

FIGURE 17 TRANSMISSION LOSS AS FUNCTION OF INCIDENT ANGLE AT 400 kHz FOR ABS MATERIAL

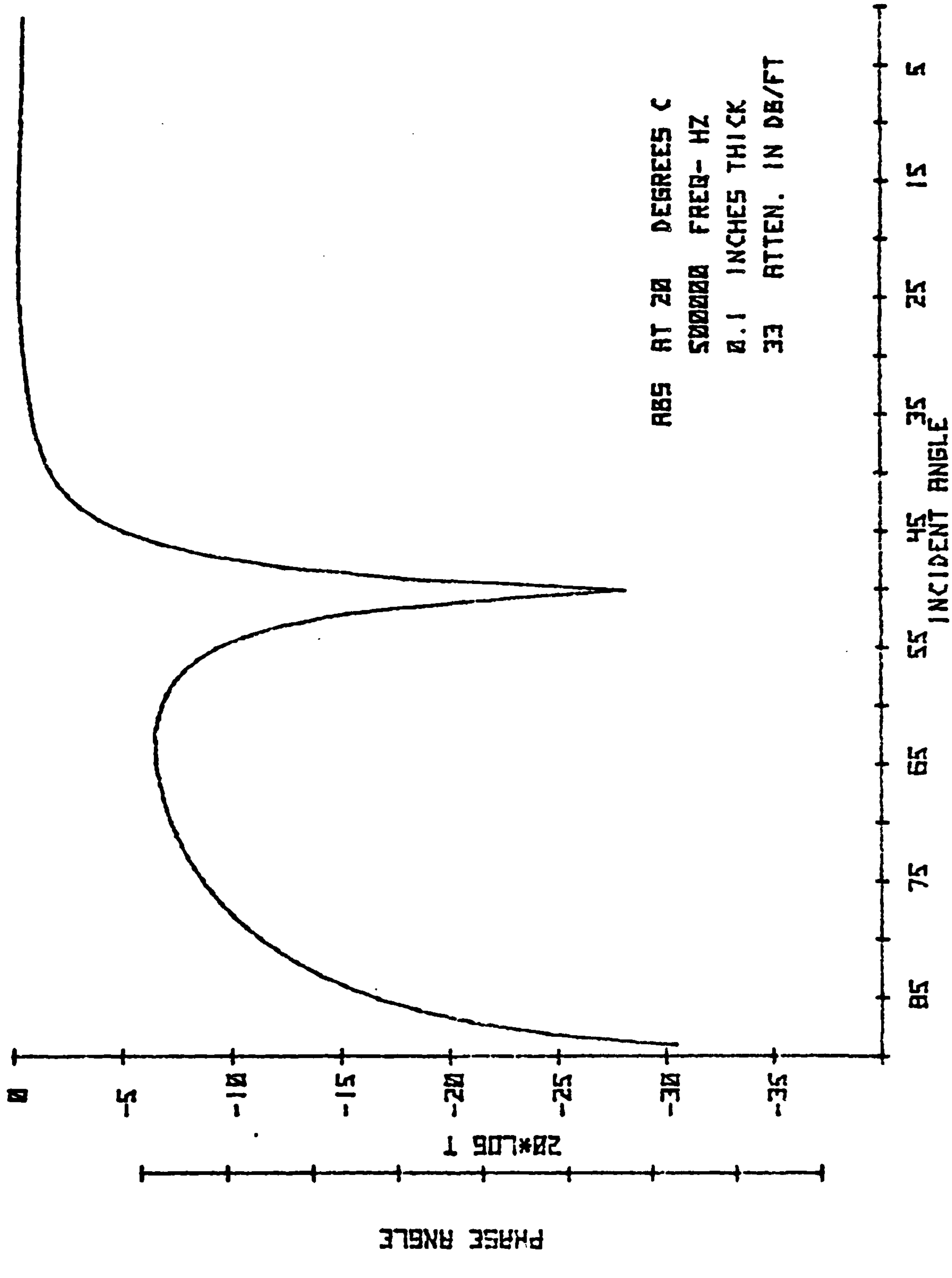

FIGURE 18 TRANSMISSION LOSS AS FUNCTION OF INCIDENT ANGLE AT 500 kHz FOR ABS MATERIAL

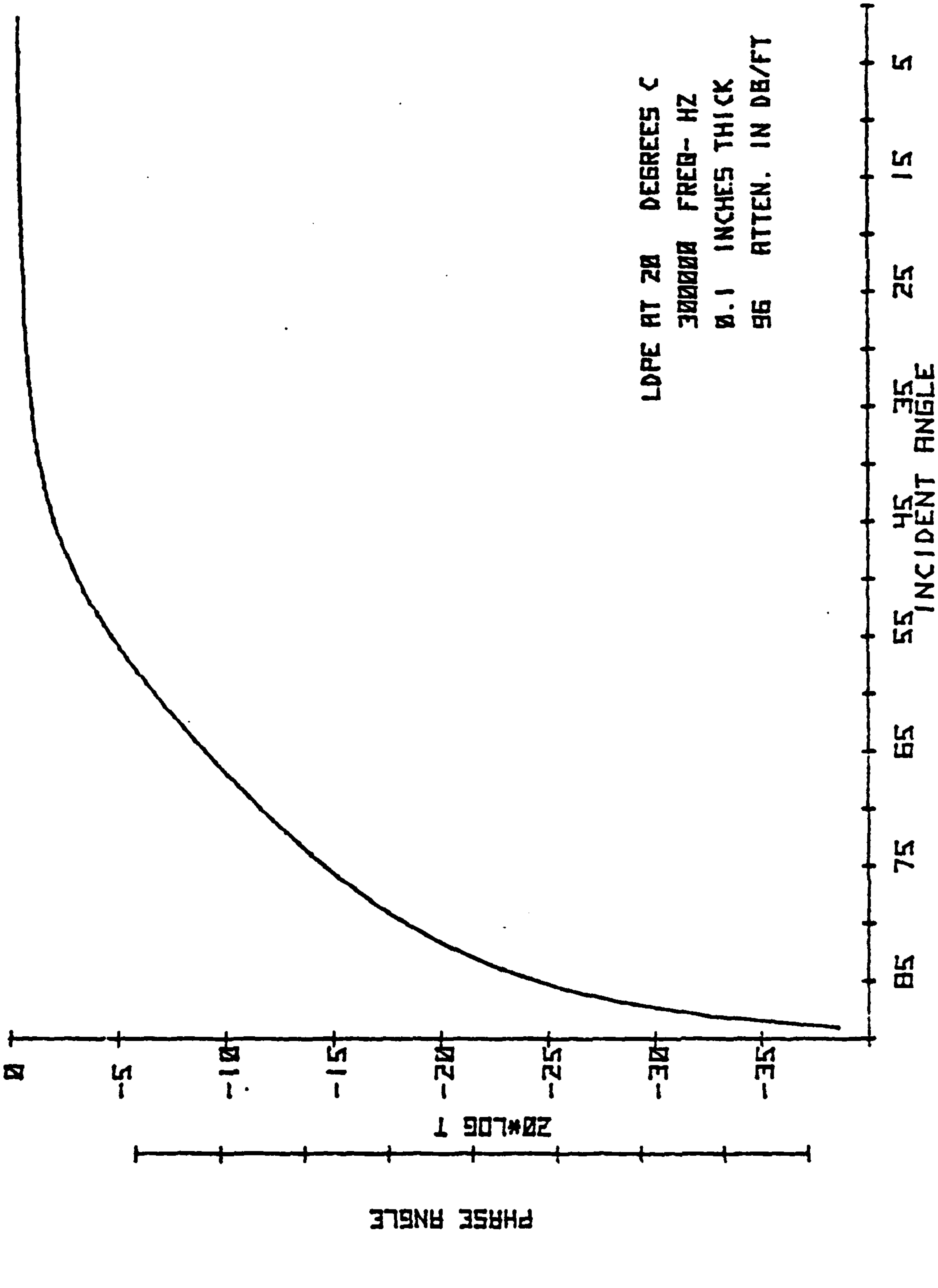

FIGURE 19 TRANSMISSION LOSS AS FUNCTION OF INCIDENT ANGLE AT 20°C FOR LOW-DENSITY POLYETHYLENE MATERIAL

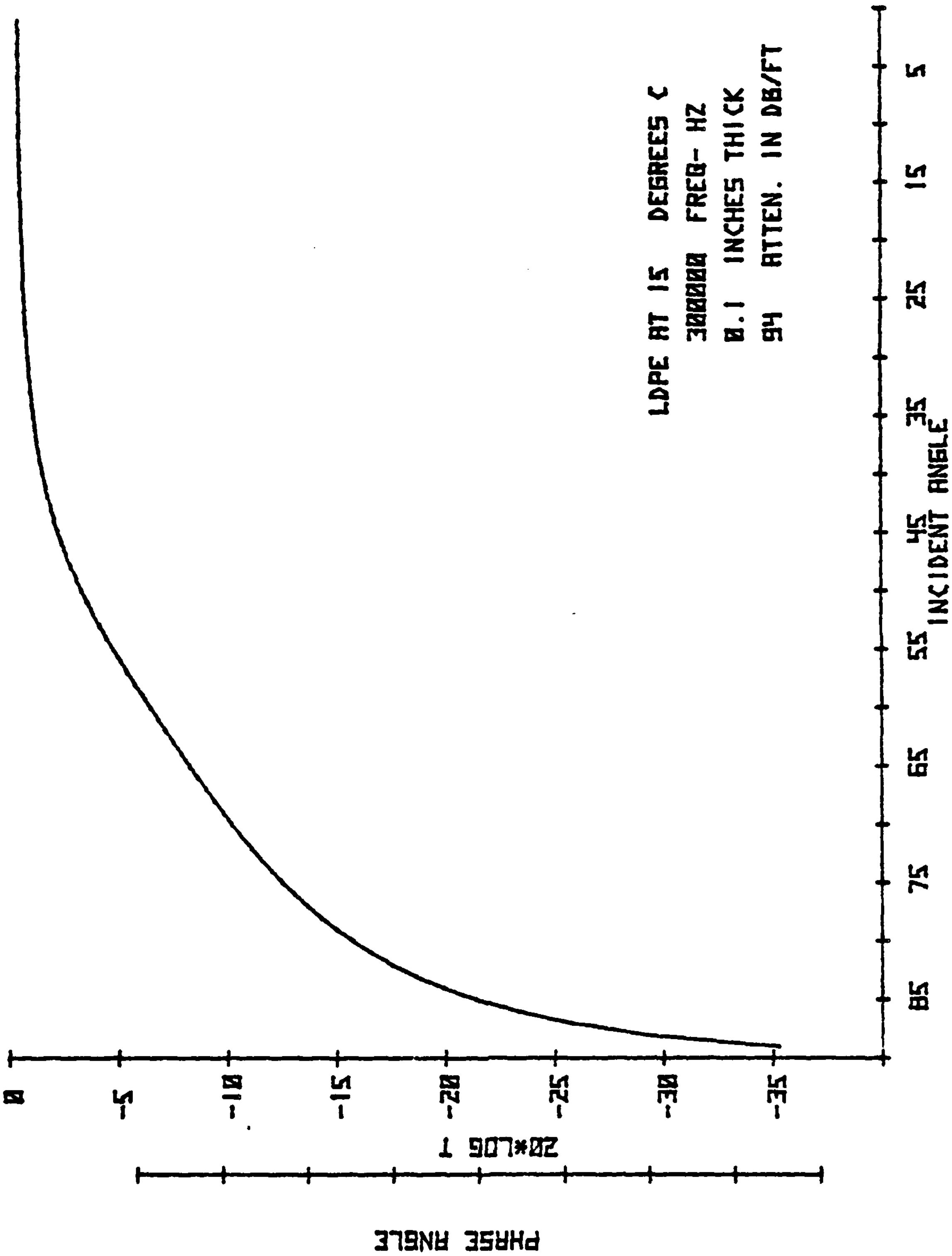

FIGURE 20 TRANSMISSION LOSS AS FUNCTION OF INCIDENT ANGLE AT 15°C FOR LOW-DENSITY POLYETHYLENE MATERIAL

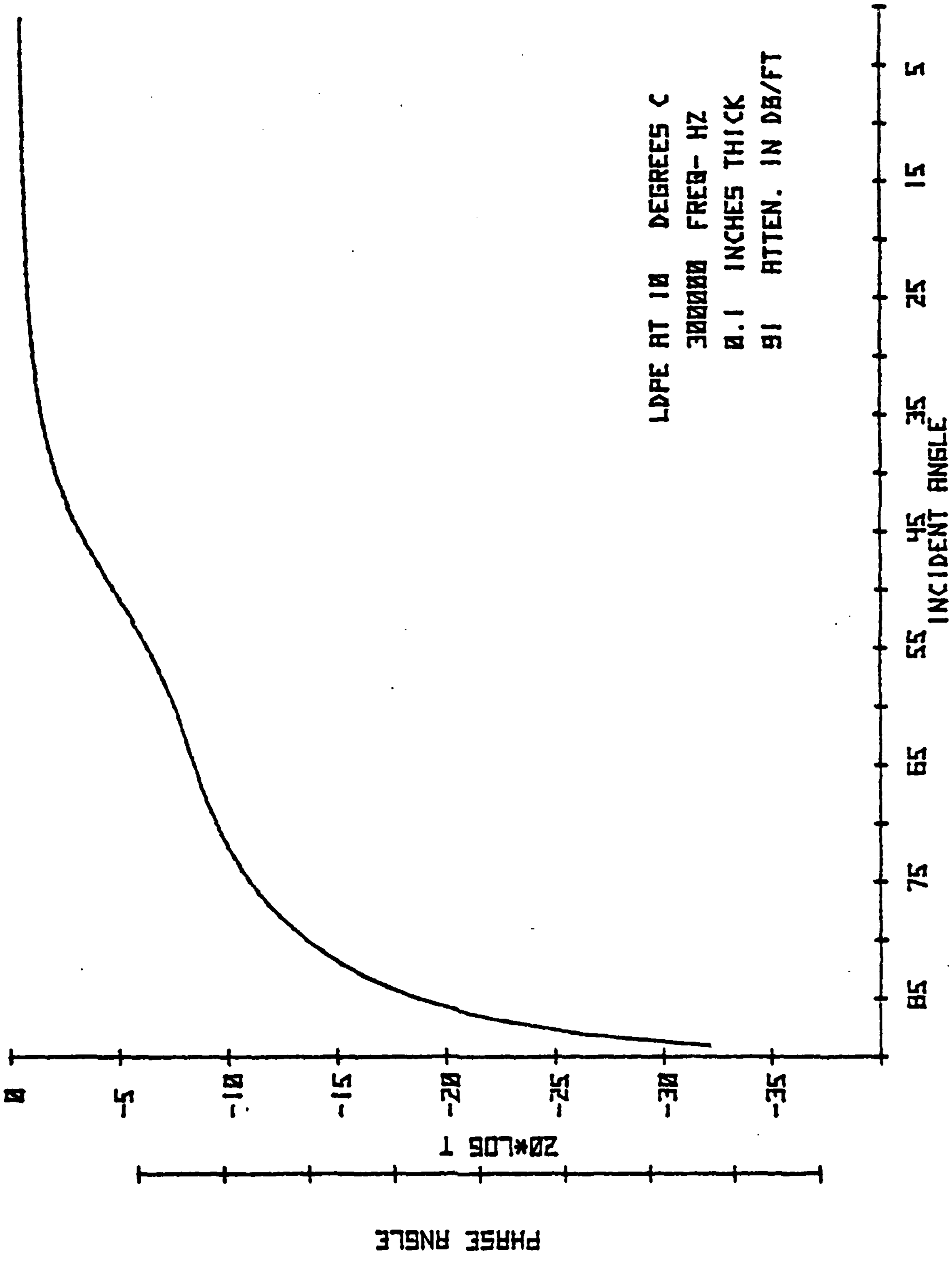

FIGURE 21 TRANSMISSION LOSS AS FUNCTION OF INCIDENT ANGLE AT 10°C FOR LOW-DENSITY POLYETHYLENE MATERIAL

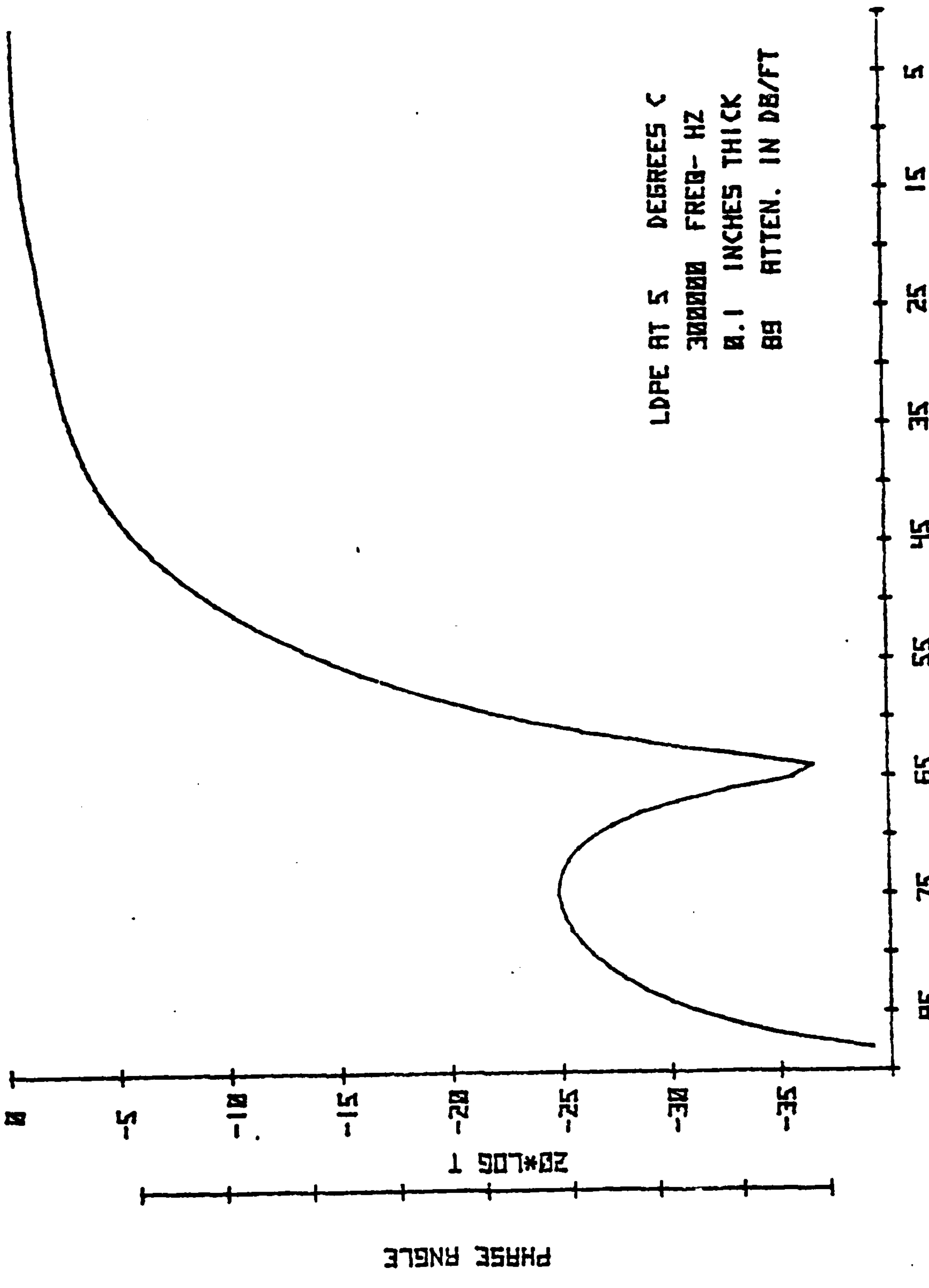

FIGURE 22 TRANSMISSION LOSS AS FUNCTION OF INCIDENT ANGLE AT 5°C FOR LOW-DENSITY POLYETHYLENE MATERIAL

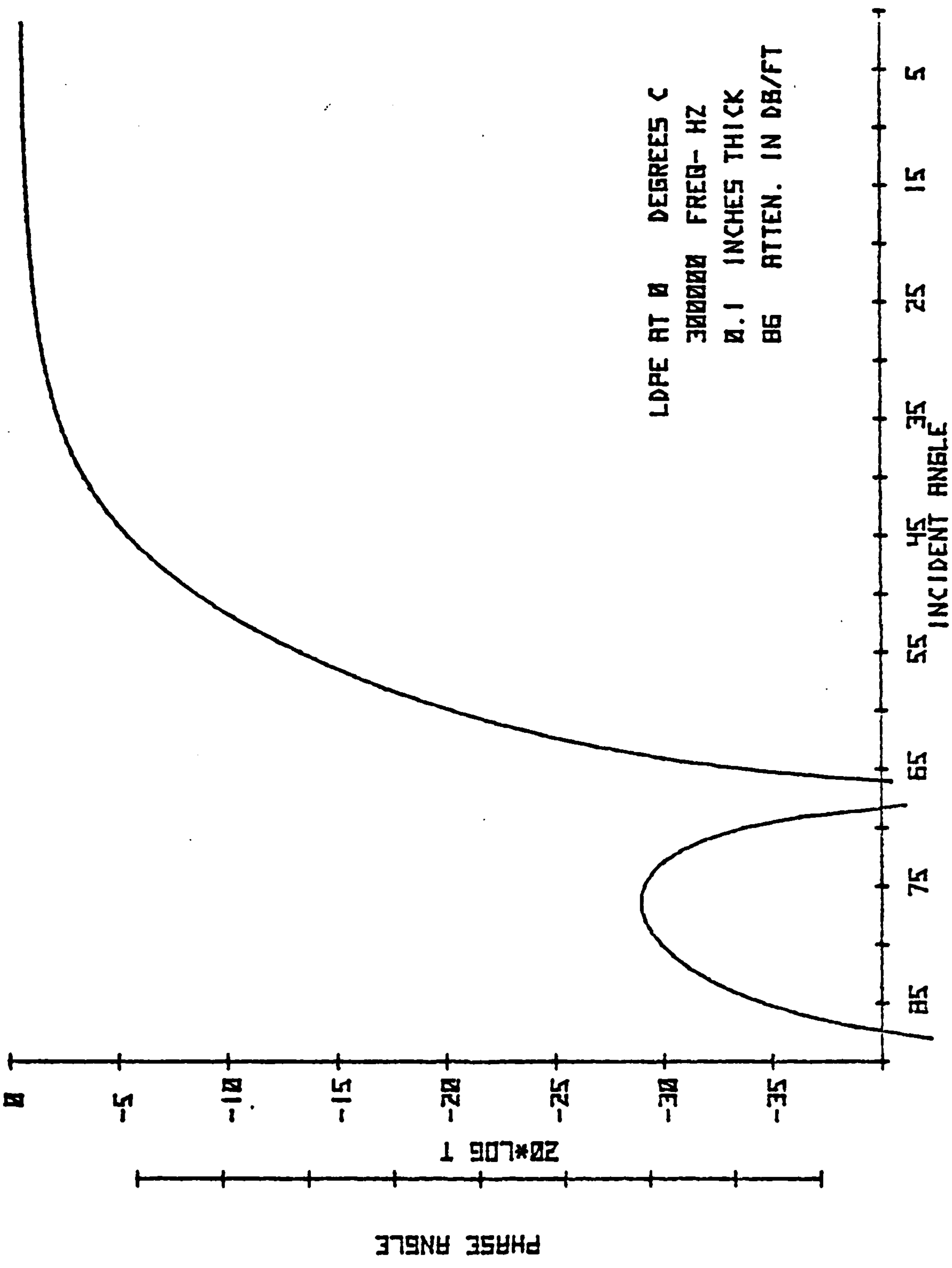

FIGURE 23 TRANSMISSION LOSS AS FUNCTION OF INCIDENT ANGLE AT 0°C FOR LOW-DENSITY POLYETHYLENE MATERIAL

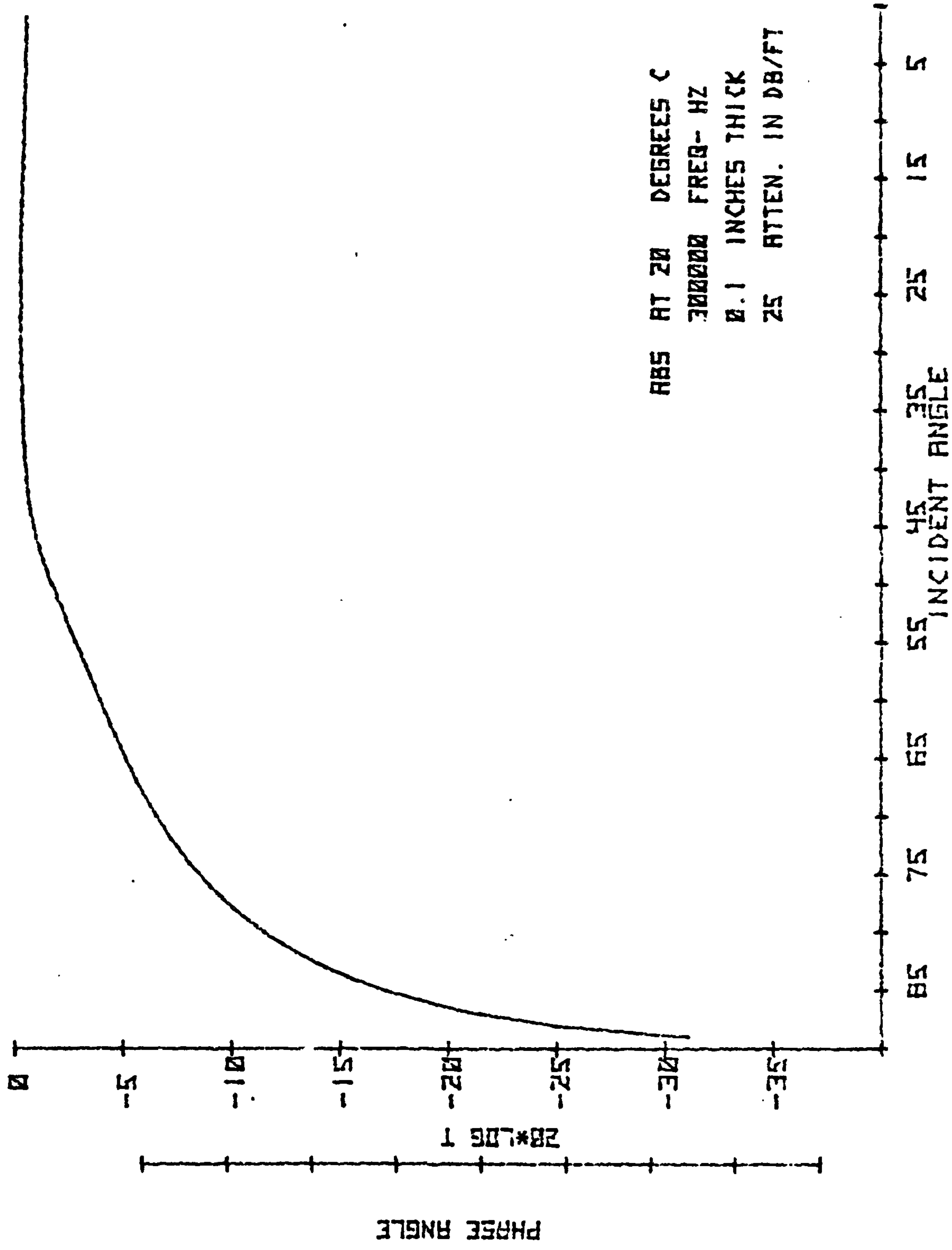

FIGURE 24 TRANSMISSION LOSS AS FUNCTION OF INCIDENT ANGLE AT 20°C FOR ABS MATERIAL

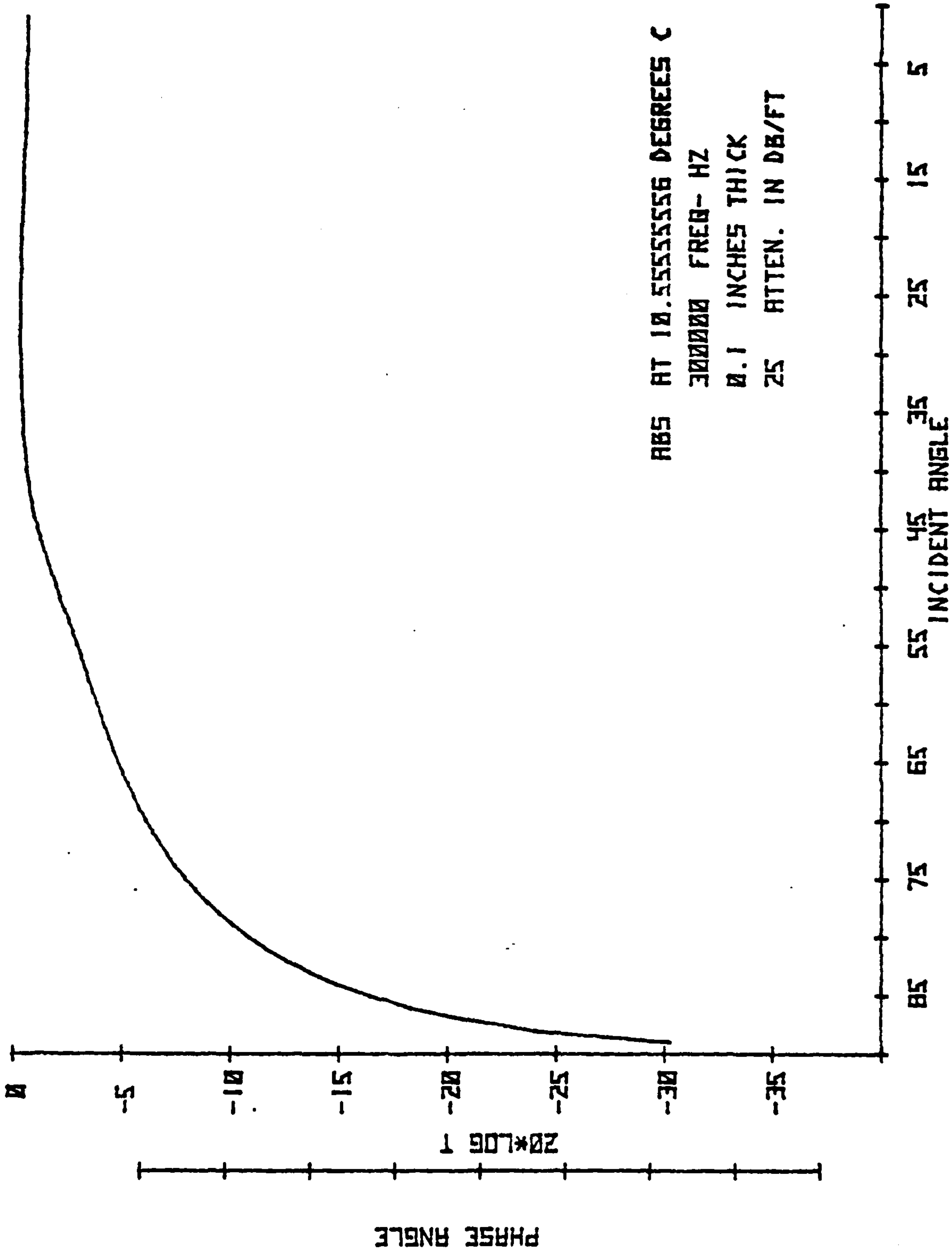

FIGURE 25 TRANSMISSION LOSS AS FUNCTION OF INCIDENT ANGLE AT 10.5°C FOR ABS MATERIAL

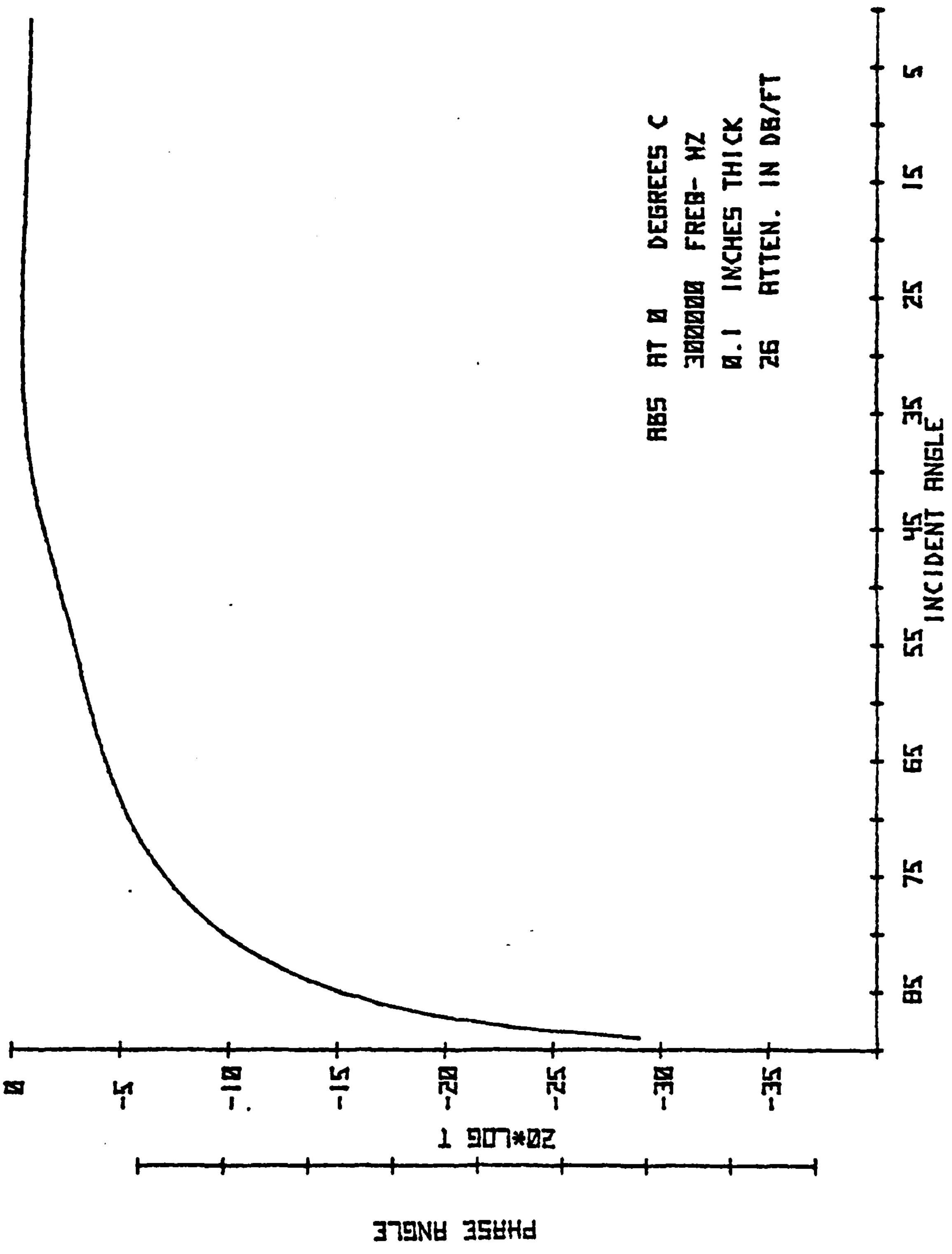

FIGURE 26 TRANSMISSION LOSS AS FUNCTION OF INCIDENT ANGLE AT 0°C FOR ABS MATERIAL

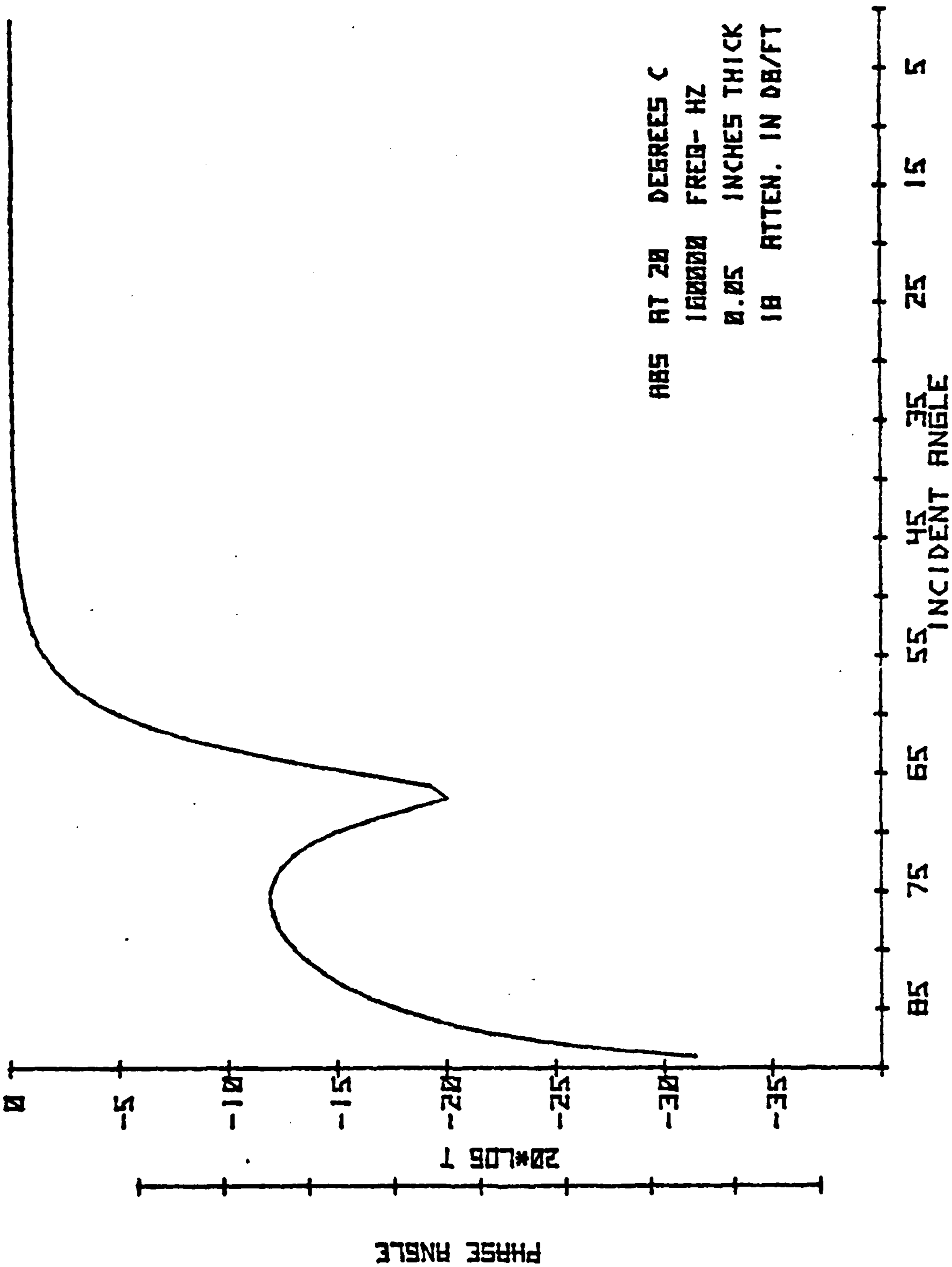

FIGURE 27 TRANSMISSION LOSS AS FUNCTION OF INCIDENT ANGLE FOR .05 INCH-THICK ABS MATERIAL

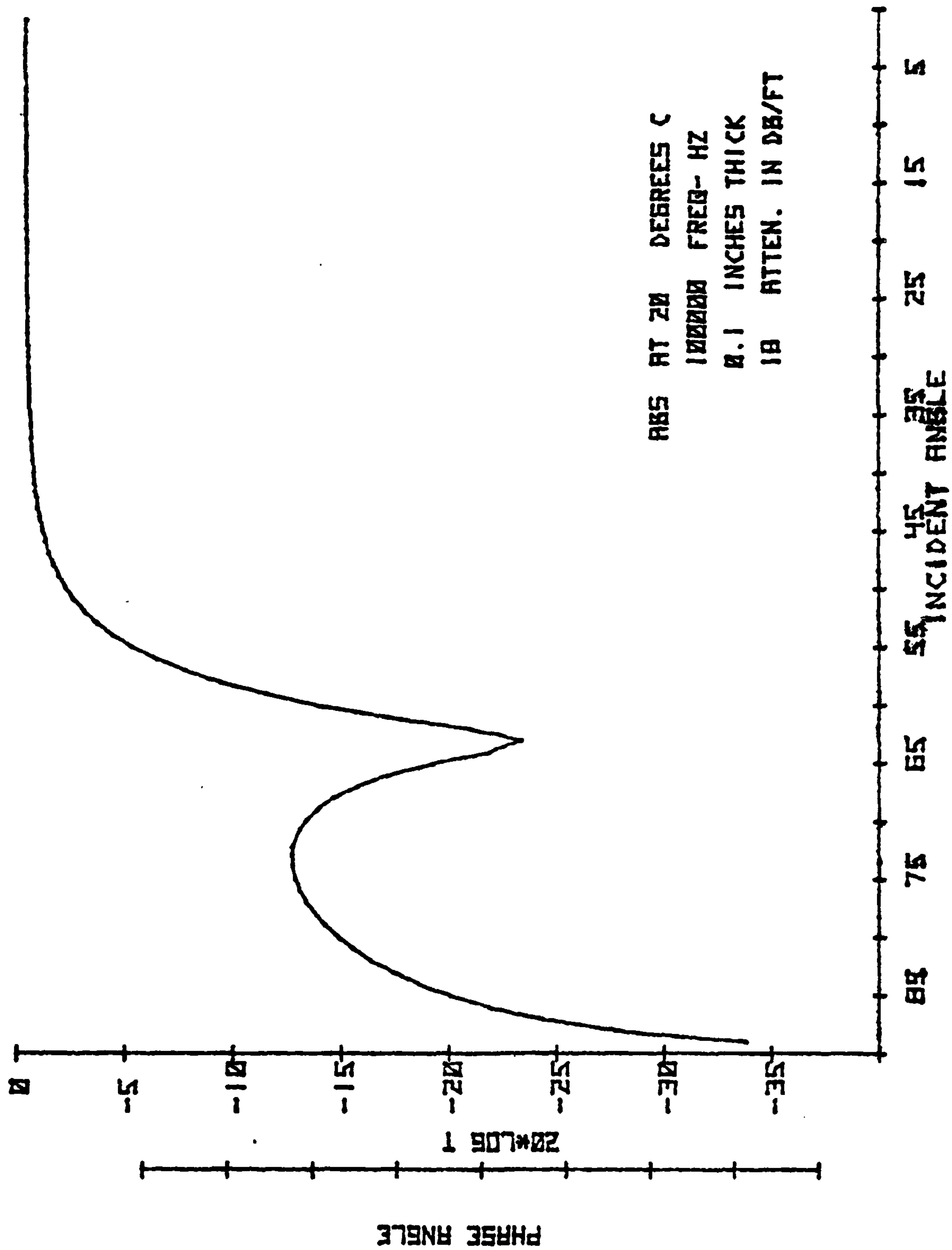

FIGURE 28 TRANSMISSION LOSS AS FUNCTION OF INCIDENT ANGLE FOR .1 INCH-THICK ABS MATERIAL

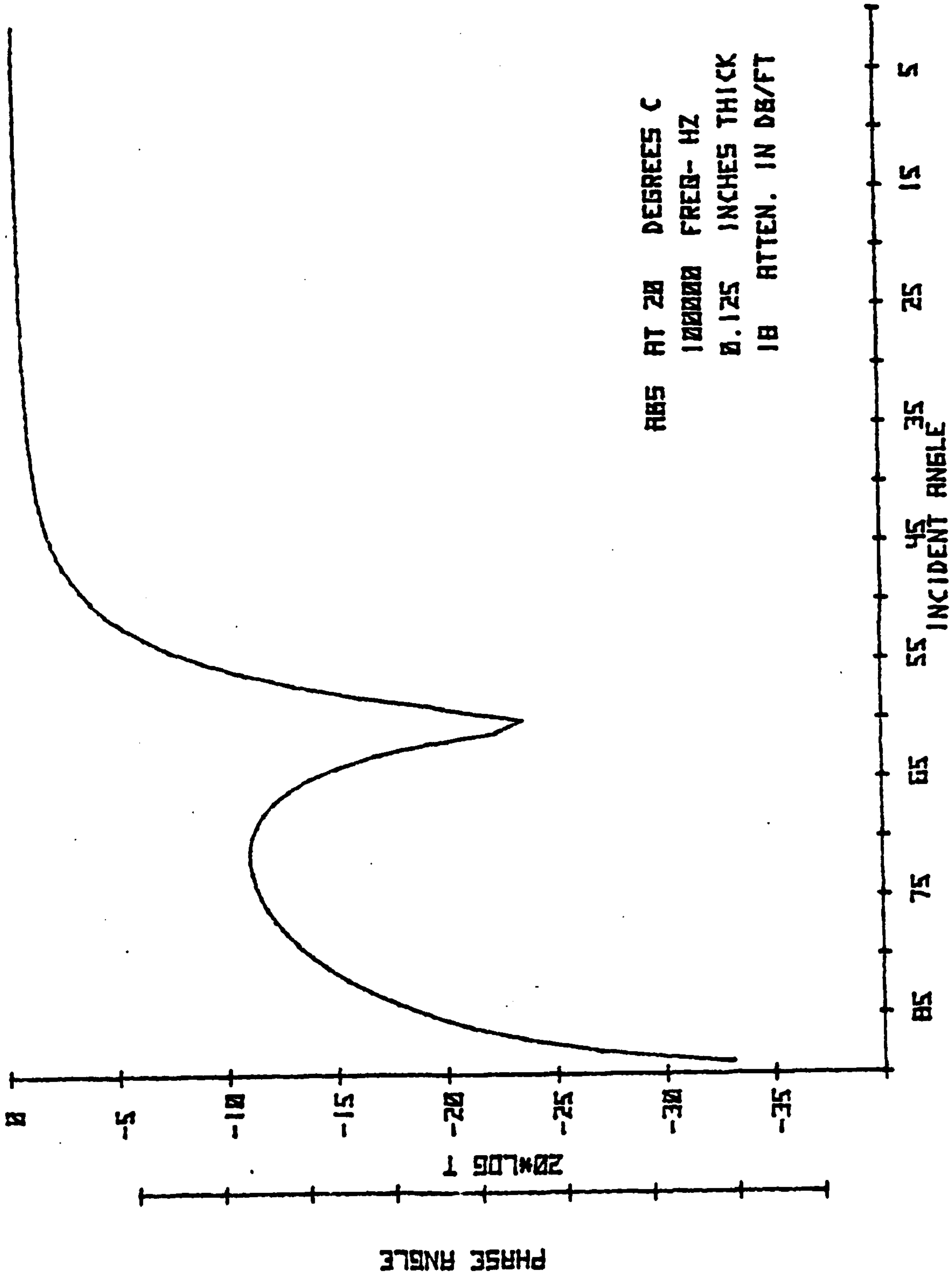

FIGURE 29 TRANSMISSION LOSS AS FUNCTION OF INCIDENT ANGLE FOR .125 INCH-THICK ABS MATERIAL

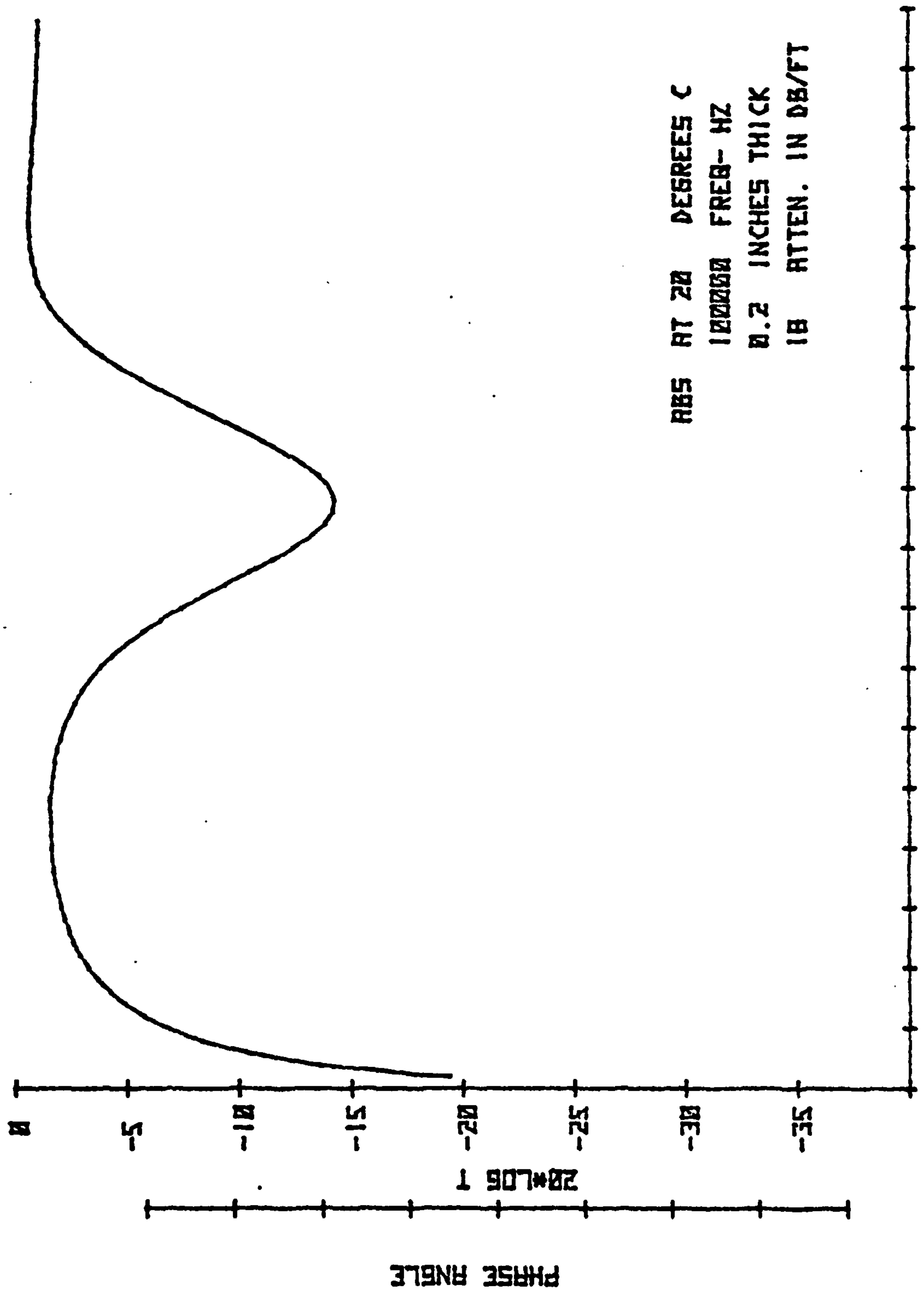

FIGURE 30 TRANSMISSION LOSS AS FUNCTION OF INCIDENT ANGLE FOR .2 INCH-THICK ABS MATERIAL

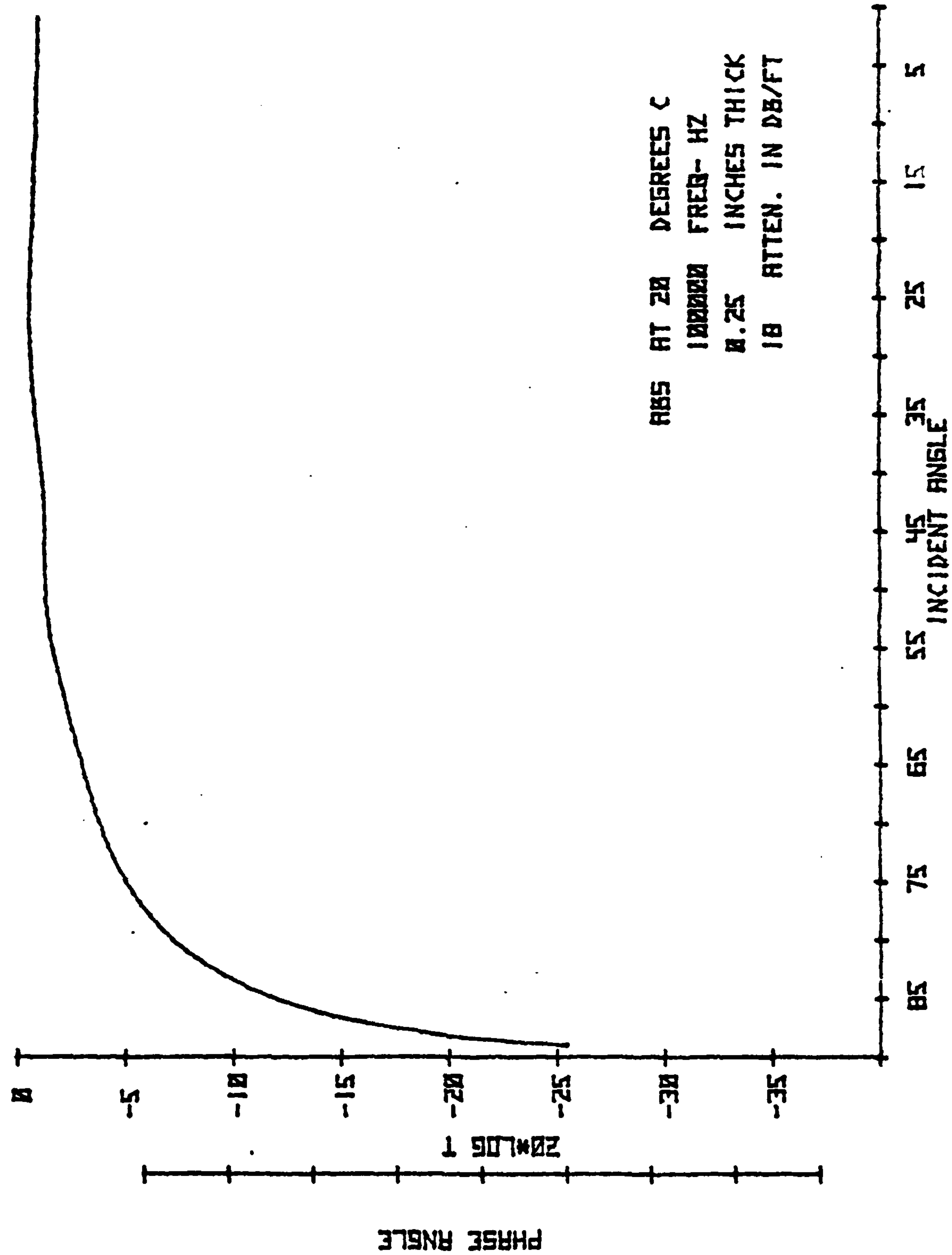

FIGURE 31 TRANSMISSION LOSS AS FUNCTION OF INCIDENT ANGLE FOR .25 INCH-THICK ABS MATERIAL

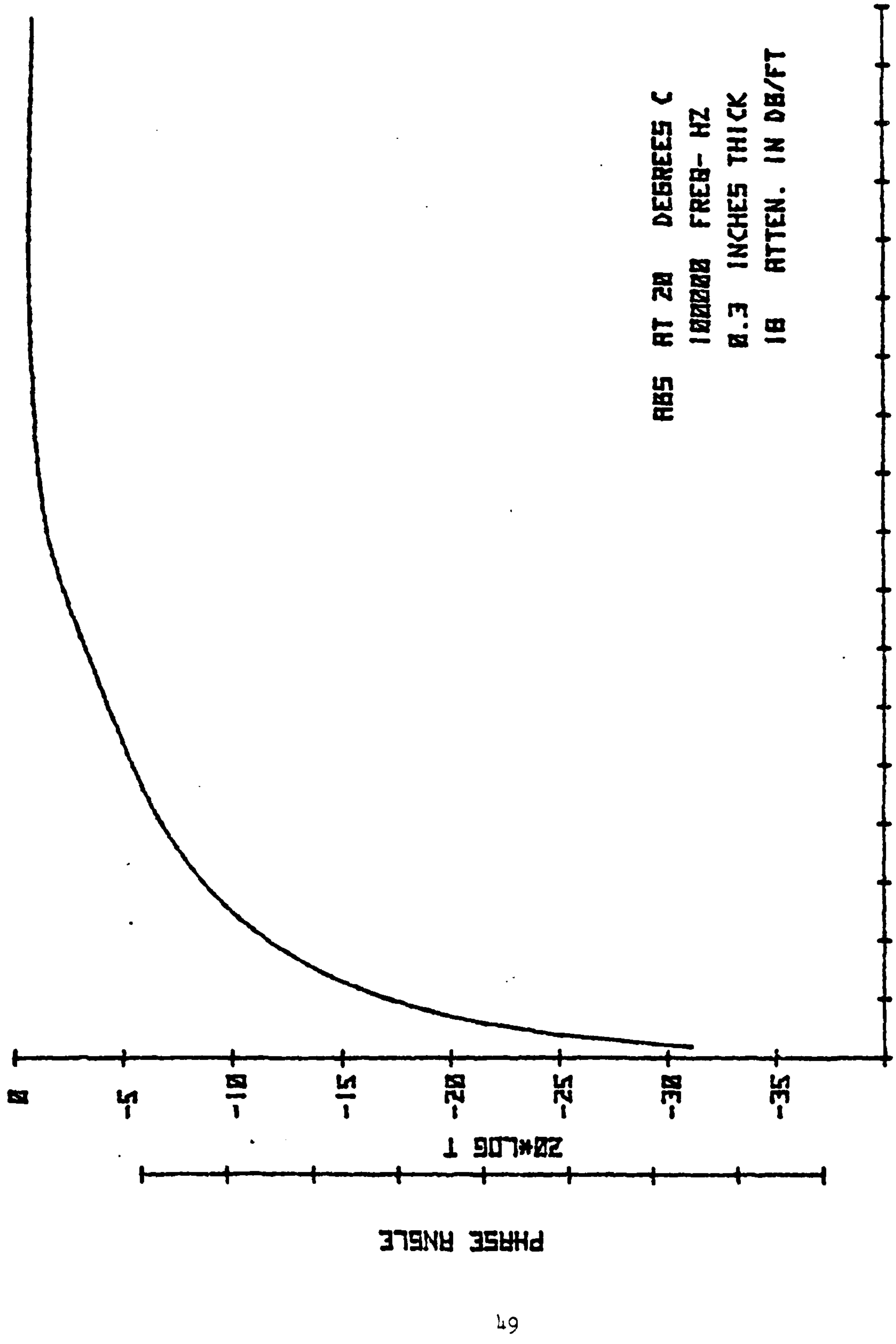

FIGURE 32 TRANSMISSION LOSS AS FUNCTION OF INCIDENT ANGLE FOR .3 INCH-THICK ABS MATERIAL

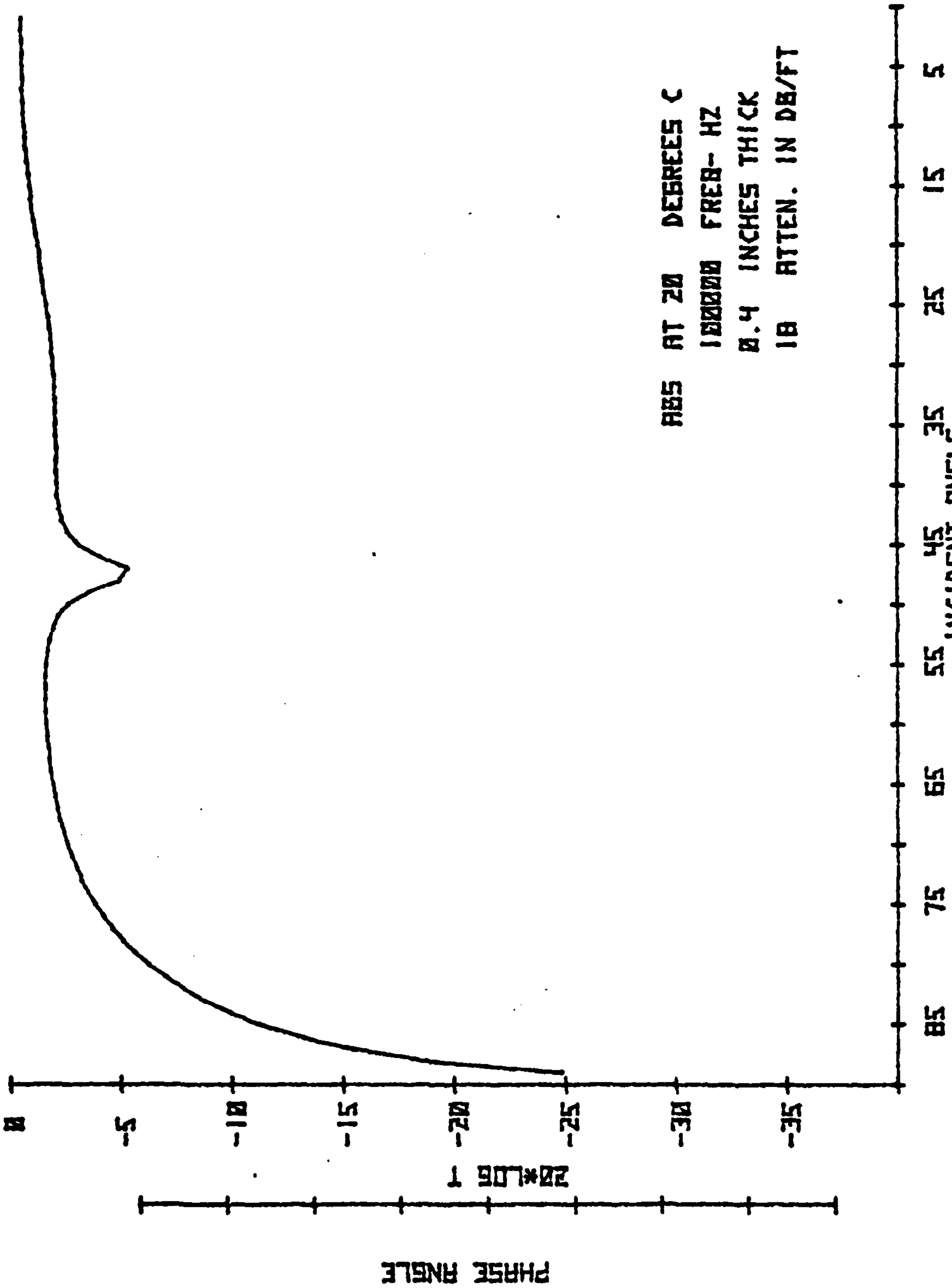

FIGURE 33 TRANSMISSION LOSS AS FUNCTION OF INCIDENT ANGLE FOR .4 INCH-THICK ABS MATERIAL

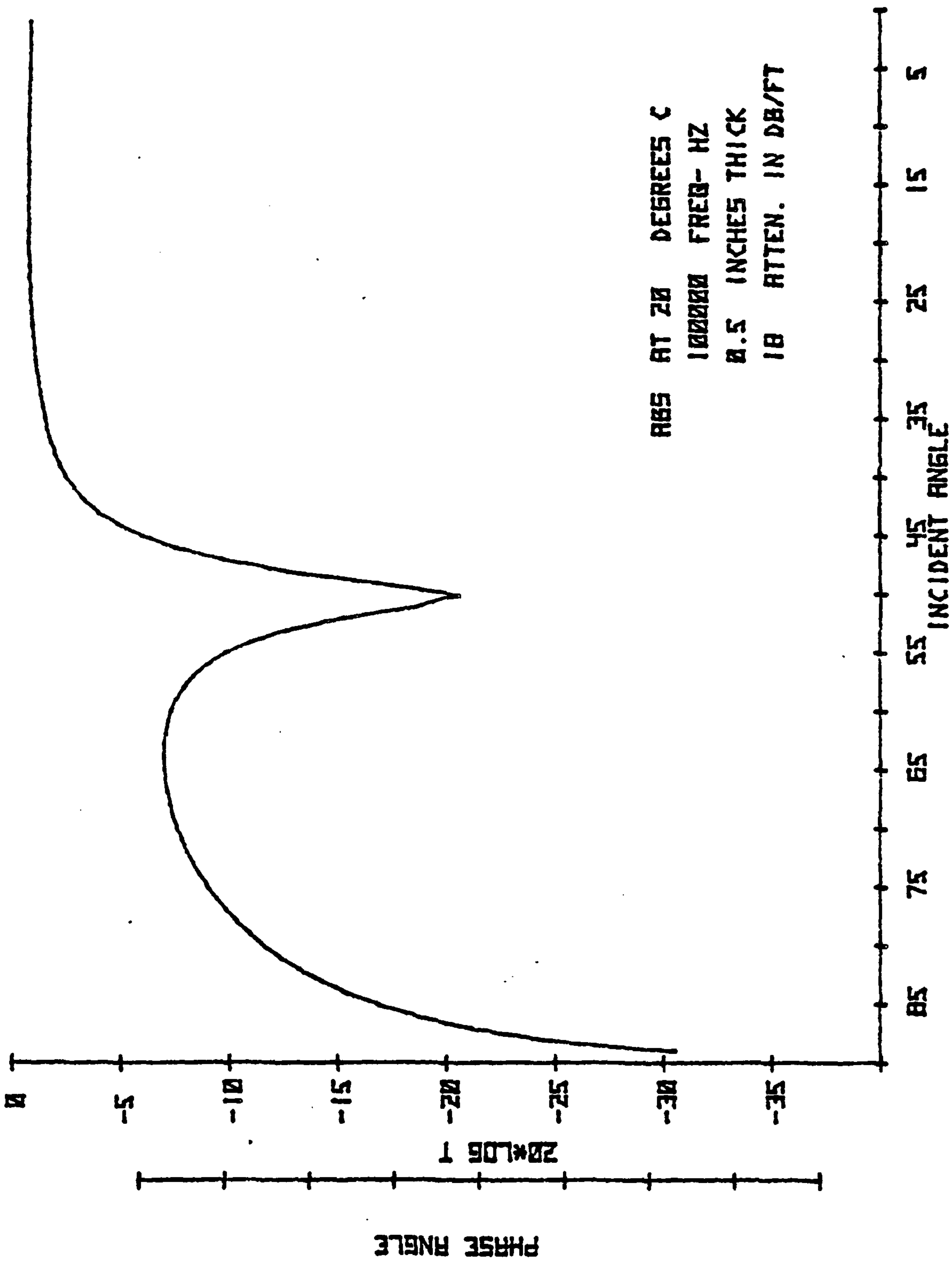

FIGURE 34 TRANSMISSION LOSS AS FUNCTION OF INCIDENT ANGLE FOR .5 INCH-THICK ABS MATERIAL

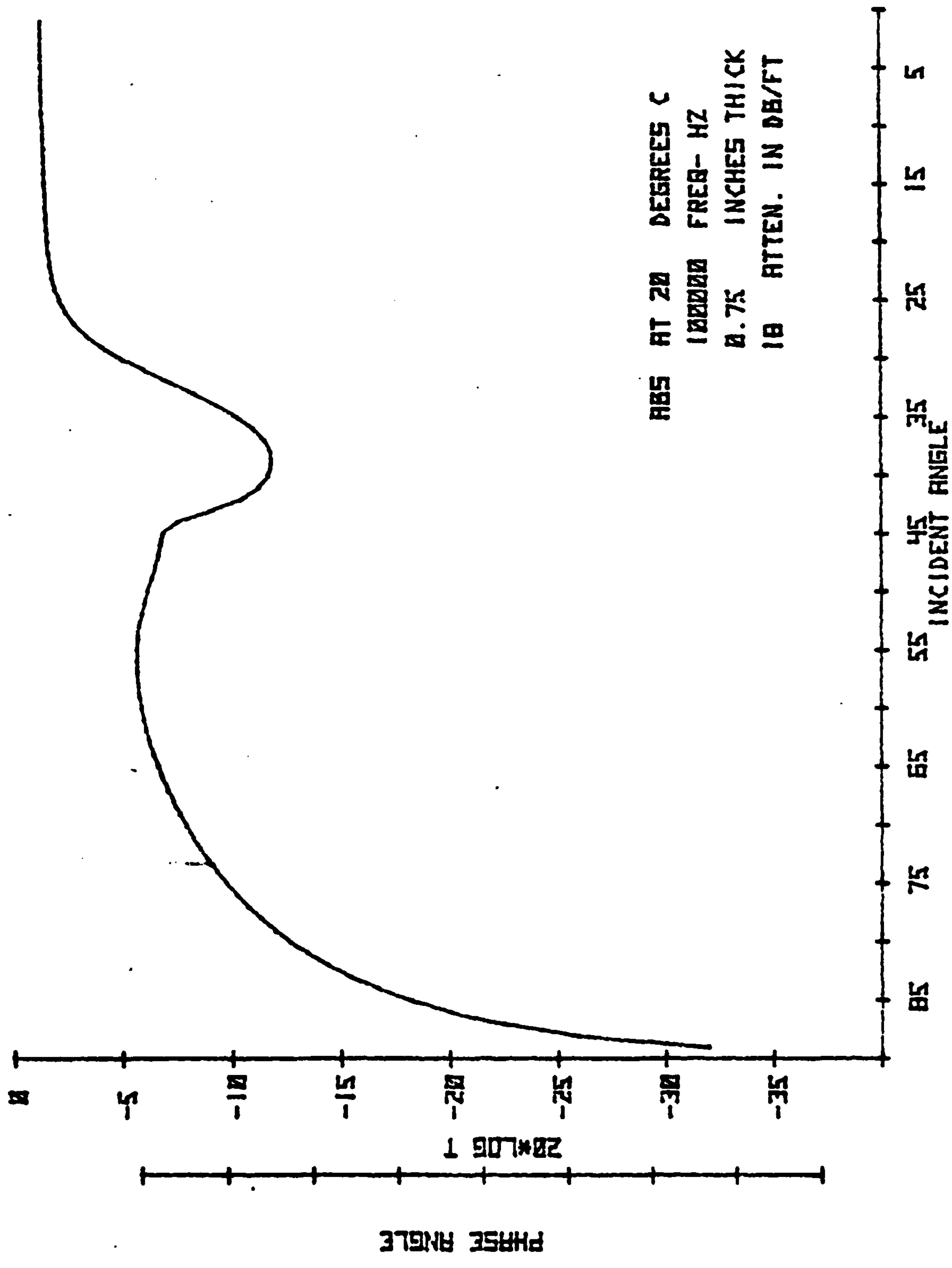

FIGURE 35 TRANSMISSION LOSS AS FUNCTION OF INCIDENT ANGLE FOR .75 INCH-THICK ABS MATERIAL

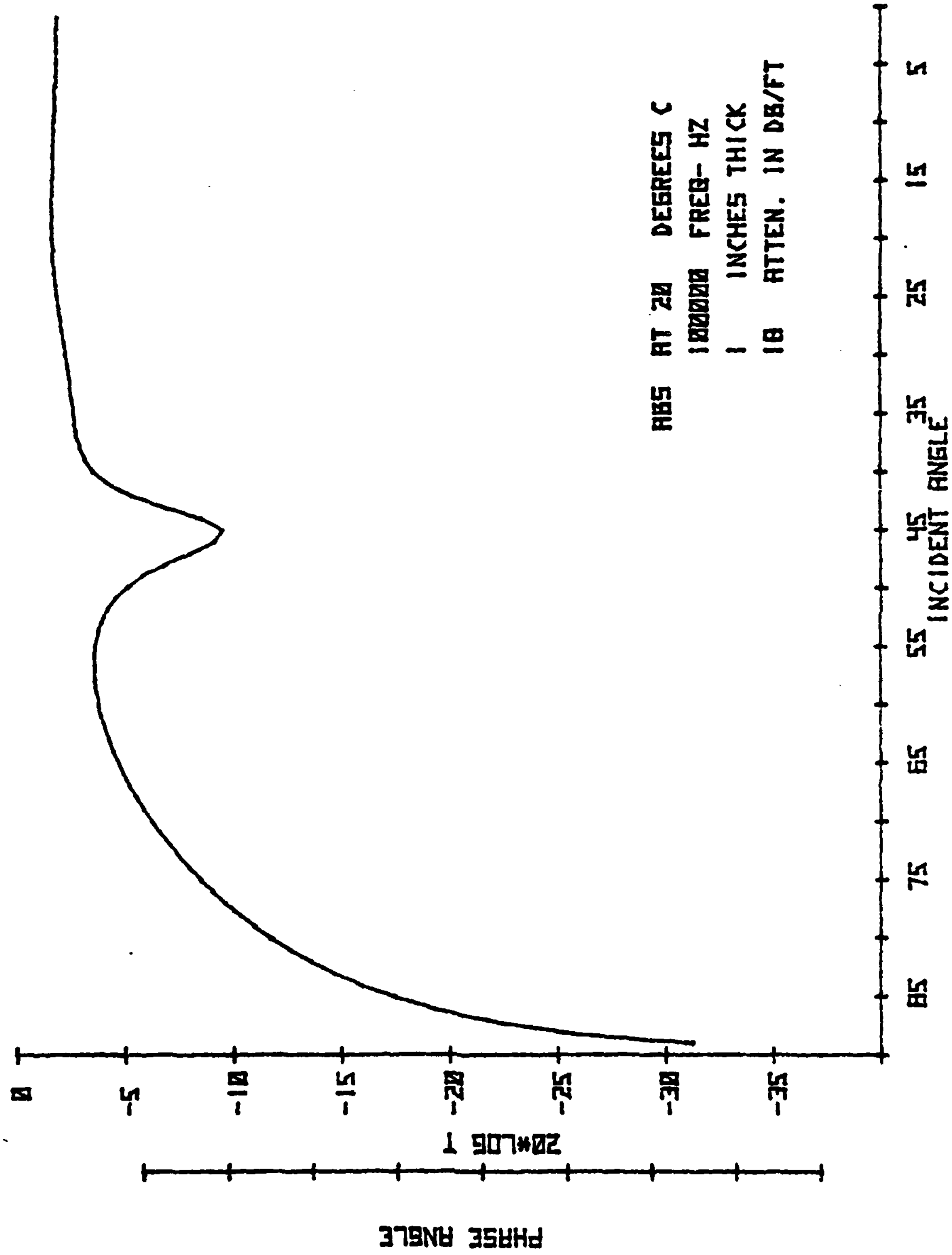

FIGURE 36 TRANSMISSION LOSS AS FUNCTION OF INCIDENT ANGLE FOR 1 INCH-THICK ABS MATERIAL

TABLE 1 MATERIAL PARAMETERS USED IN THEORETICAL CALCULATIONS[3,7]

Material	Longitudinal velocity c (m/sec)	Shear velocity b (m/sec)	Longitudinal absorption α (dB/m 100 kHz)	Shear absorption β [dB/(mkHz)]	ρ Density (g/cm^3)	$-\frac{dc}{dt}$ (m/sec deg)	$-\frac{db}{dt}$ (m/sec deg)
Absonic-A	2100	880	50	0.1	1.08	3.5	0.7
Plexiglas	2600	1280	50	0.1	1.19	2.5	2.0
Low-density polyethylene	2000	445	50	0.45	0.922	5.9	4.0
High-density polyethylene	2349	736	50	0.1	0.967	9.6	6.8
Teflon	1300	460	50	0.45	2.19		
Aluminum	6420	3040	3	0	2.7		

[3] See footnote 3 on page 9.

[7] See footnote 7 on page 15.

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